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ABSTRACT OF DISSERTATION

Molly Rebecca Winke

The Graduate School
University of Kentucky
2007

PRECOOLING AND RUNNING ECONOMY

ABSTRACT OF DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Education at the University of Kentucky

By
Molly Rebecca Winke

Lexington, Kentucky

Director: Dr. J. W. Yates, Associate Professor of Exercise Physiology

Lexington, Kentucky

2007

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ABSTRACT OF DISSERTATION

PRECOOLING AND RUNNING ECONOMY

Precooling, or a reduction in core temperature (T_c) has been demonstrated to be a potent enhancer of endurance running performance, however there is no known mechanism for this improvement. By holding the exercise workload constant, changes in variables such as running economy (RE), heart rate, and ventilation (V_E) can be determined as a result of precooling. Improved running economy, or a reduced oxygen cost of a specific workload, is linked to improved exercise performance. **Purpose:** To determine the changes in flexibility, RE, heart rate, V_E , and T_c during running at a constant workload following cool water immersion and to determine any sex-specific responses. **Methods:** Fourteen well-trained runners (8 males and 6 females) completed four treadmill runs at a sex-specific velocity (8.0 mph for females and 8.6 mph for males). The first two runs served as accommodation trials. The third and fourth runs were preceded by either cool water immersion (24.8°C) for 40 minutes or quiet sitting. Oxygen consumption, heart rate, T_c , V_E , and flexibility were measured during both experimental trials. **Results:** Running economy did not change as a result of the precooling treatment, whereas T_c and heart rate were reduced by 0.4°C and 5 beats per minute, respectively. Minute ventilation was reduced in the female subjects only (1.4 liters/min). Sex differences were apparent in T_c , heart rate, V_E , and flexibility response. **Conclusion:** While the precooling procedure was effective in reducing T_c and heart rate, RE did not change. Thus, improvements in RE cannot explain the dramatic enhancements of endurance running performance that often occur post-cooling. Differences between male and female subjects in response to precooling were identified, most notably in V_E .

KEYWORDS: Precooling, Running Economy, Core Temperature, Submaximal Running, Lower-body Flexibility

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October 10, 2007

PRECOOLING AND RUNNING ECONOMY

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DISSERTATION

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Chapter I

Introduction

Typically, a thorough warm-up is advocated prior to any physical activity to increase body temperature, improve muscular efficiency, and reduce the risk of injury due to exercise. However, multiple investigators have demonstrated significant and often dramatic improvements in performance due to the opposite practice, precooling. As the name suggests, precooling is the reduction of core temperature (T_c) via exposure to cold air, cold water, or the use of commercially-available cooling vests. After cold exposure and a reduction in T_c , mean time to exhaustion has improved up to 37% (25) and work rate during a time trial protocol has improved up to 17% (14) when compared to a control condition. These results have been demonstrated in both hot and humid environments as well as normal conditions. In fact, improvements due to precooling are so profound that no study investigating the effects of precooling on endurance running performance has failed to demonstrate a significant increase in performance (1, 6, 33, 53, 54, 59).

Although the resulting performance improvements have been demonstrated in multiple studies, the metabolic factors responsible for this improvement have been equivocal. In general, precooling is thought to be effective by reducing the body's thermal strain, requiring less blood flow to the skin for cooling purposes and allowing a larger portion of the blood volume to be available for the working musculature. Thus, when compared to a non-cooled trial, precooling should reduce heart rate and lactate production, an exercise by-product associated with fatigue. While some evidence supports this hypothesis, a considerable amount of evidence does not. No study utilizing an endurance protocol has demonstrated a decreased lactate production after precooling (7, 21, 30, 33), although one study has demonstrated an increase in this variable (6). A reduction in heart rate has been noted in several studies, although this effect can be transient and eliminated within the first minutes of

the exercise protocol (6, 14, 18, 26, 27, 47, 59). Clearly, other factors beyond a reduction in heart rate and lactate production are responsible for the dramatic improvements in endurance performance.

To determine an improvement in performance, investigators measure either time to complete a given distance, commonly referred to as a time trial, or time to exhaustion. Six studies have examined only the metabolic changes resulting from precooling and did not include a performance variable such as time to exhaustion or time to complete a given distance (4, 7, 18, 21, 22, 58). Instead, metabolic and perceptual variables such as oxygen consumption (VO_2), lactate production, heart rate, ratings of perceived exertion, muscle metabolite content, and substrate content were compared between a precooled and a non-cooled trial. These studies failed to find a significant difference in any tested variable with the exception of heart rate (7, 18, 22, 58). Thus, the metabolic consequences of precooling remain unknown.

To date, only two studies have specifically investigated the effects of precooling on exercise economy, or the oxygen consumption (VO_2) required to sustain a submaximal workload (18, 22). A lower oxygen cost would indicate an improvement in the ability of the body to perform the given workload. Previous work has resulted in insignificant findings regarding mean VO_2 values, however these studies were not properly designed to measure economy. Running economy (RE) can vary up to 30% among athletes with similar maximal oxygen consumption ($\text{VO}_{2\text{max}}$) values running at the same speed (19). Additionally, RE can vary within a given individual up to 5% (40, 41) with more highly trained individuals expressing lower variability. Thus to reduce intra-individual variability, it has been suggested that subjects complete 60 minutes of treadmill accommodation divided into two sessions (11, 39, 46) and to determine RE by averaging the RE value of two trials (57). Thus, to investigate the effects of precooling on RE, additional accommodation trials must be included in the study design, which the few studies measuring economy have not included.

How might precooling impact RE? A higher T_c increases oxygen consumption at a given speed (34), thus a lowered T_c is likely to reduce oxygen cost and thereby improve RE. An additional variable that has been linked to RE is flexibility. Jones (31) found a significant relationship between aerobic demand at 16.0 kilometers per hour (km/hr) and sit-and-reach score, a measure of lower body flexibility. In other words, the least flexible runners were the most economical. Data from Craib et al. (16) lend support to this finding. These authors found that ankle flexibility ($r = 0.65$) and hip flexibility ($r = 0.53$) were positively associated with VO_2 at $4.13 \text{ m}\cdot\text{s}^{-1}$ (14.0 km/hr) again indicating that the least flexible runners demonstrated the best economy. However, five other measures of flexibility, including sit and reach score, were not significantly associated with RE.

Exposure to cold water is also likely to increase the perception of muscular stiffness and reduce flexibility of the exposed area. A reduction in flexibility may be associated with an improved running economy and running performance. Thus, in addition to delaying thermal-associated increases in oxygen cost, precooling may also influence RE by modifying lower body flexibility.

An additional purpose of this study is to investigate sex differences in response to precooling and to compare RE values between men and women. Few precooling studies have included both male and female subjects. Schmidt and Bruck (47) were the only investigators to mention a potential sex difference in response to precooling. In this study, precooling did not significantly improve performance on an incremental cycling test to exhaustion in all subjects. However, the three subjects that did improve total work, time to exhaustion, and work rate were all female. No study has attempted to determine the relationship between sex and the response to precooling.

While it is clear that precooling is an effective strategy for improving endurance performance, more work is necessary to determine the physiological consequences of a reduced T_c . Exercise economy has been studied as the variable of interest infrequently, and to do so would require additional treadmill

accommodation sessions and multiple RE trials to reach a representative value from each subject. Precooling may also modify lower body flexibility in addition to RE, which would suggest changes in the mechanical properties of the muscle fibers may be contributing to the improvements in running performance. In addition, the role of sex and the response to precooling has yet to be studied.

Statement of Problem

While precooling has been demonstrated to be a potent enhancer of endurance exercise performance, the mechanisms underlying these improvements remain unknown. Most studies have been designed to measure changes in performance, not changes in specific metabolic variables. In studies that utilize a time trial format, which allows the athlete to self-select a work rate, direct comparisons between variables measured during the precooled and non-cooled trials cannot be made due to the variation in work rate. For example, heart rate may be lower in one condition when compared to another, however, the difference in heart rate may be due to a lower work rate, lower body temperature, or a combination of both variables. Performance has also been measured by time to exhaustion at a specific workload. While this format addresses the issue of work rate variability, time to exhaustion is not a practical measure of performance. Other variables such as internal motivation and mental drive ultimately determine performance, not body temperature.

Perhaps one way to monitor changes in metabolic variables is to have the athlete perform trials of the same workload and duration under precooled and non-cooled conditions. This allows for direct comparisons of relevant variables without undue psychological influence from lengthy exercise trials without a predetermined end point. In addition, measurement of oxygen consumption at a specified workload, also referred to as exercise economy, requires additional accommodation sessions to reduce variability in this measure. Previous authors have suggested sixty minutes of treadmill accommodation to minimize variability in running economy (11, 39, 46). Intra-individual variation in running economy is also known to be lower in well-trained athletes (40).

Previous studies examining precooling and the effects on endurance performance have typically involved only male subjects. Of the 20 studies investigating precooling and endurance exercise performance, only five have included female subjects. Why have investigators chosen to exclude female subjects? Perhaps the considerable fluctuations in T_c (up to 0.5°C) with varying

phases of the menstrual cycle and progesterone exposure have discouraged previous researchers from including female subjects (29, 50). Of the studies that have included female volunteers, no study to date has made any attempt to control for variation in T_c that occurs during the menstrual cycle. Thus, it remains unclear whether male and female subjects respond similarly to a precooling stimulus and whether resulting performance enhancements are equal among sexes.

The purpose of this study was to determine if precooling induces changes in oxygen consumption while running at a constant workload, referred to as running economy (RE), when compared to a control condition. To accurately measure RE, two treadmill accommodation sessions were conducted prior to the experimental trials to reduce intra-individual variability in oxygen consumption. Lower-body flexibility was also assessed before and after experimental sessions to determine if changes in flexibility occurred and whether these changes were related to changes in RE. Sex differences in response to precooling were also examined and all female subjects were tested during the same phase of the menstrual cycle to control for hormone-mediated changes in T_c .

Statement of Hypotheses

The test hypotheses stated that cold water immersion for forty minutes would result in the following changes when compared to a control condition:

- Significant reduction in T_c
- Significant reduction in lower-body flexibility
- Significant reduction in oxygen consumption during running at a constant workload
- Significant reduction in heart rate during the initial portion of running
- Significant correlation between the change in flexibility and the change in running economy
- Differential response to precooling between men and women

Scope of Investigation

Eighteen well-trained, sub-elite runners were recruited from the general population of Lexington, Kentucky to participate in this study. All subjects were currently engaged in run training, between 20 and 39 years of age, and free of injury that would influence running ability. Further, each subject was free of gastrointestinal, respiratory, or cardiovascular illness. All subjects were required to present recent race results to indicate their ability to complete the predetermined treadmill workload. The research reported in this investigation was initiated January 2007 and concluded in June 2007.

Assumptions

- a) The subjects represented a “well-trained” sample of runners from the area from which they came and their physical capabilities were representative of other individuals with similar run performances. It is recognized however that differences may exist between the subjects in this study and other runners with similar performances.
- b) Each subject provided maximal effort for the maximal oxygen uptake test.
- c) Each subject truthfully conformed to the exclusions stated in the “Consent to Participate in a Research Study” form (see Appendix 1) provided prior to initiation of the protocol.
- d) Each subject adhered to the provisions detailed in the “Consent to Participate in a Research Study” form specifically requesting that they would not engage in strenuous interval or resistance training prior to laboratory visits.

Delimitations

- a) Subjects were healthy, well-trained, sub-elite runners between the ages of 18 and 45 years of age.
- b) All female subjects were tested during the same phase of the menstrual cycle.
- c) Two treadmill accommodation trials were completed by each subject prior to the experimental and control sessions.
- d) Data collection was performed by the same investigator.
- e) Gas analyzers were calibrated using the same procedures prior to each use.
- f) All treadmill accommodation sessions and testing sessions were performed on the same treadmill.

Chapter II

Review of Literature

There are three purposes of this literature review. The first purpose is to examine the influence of precooling on both exercise performance and metabolic responses during exercise. The second purpose is to examine the factors that influence RE and how this variable is properly measured. Finally, a third purpose is to examine how precooling may impact RE.

Precooling and Exercise Performance

Endurance Running Protocols

Currently, six studies (see Table 2.1) have investigated the influence of precooling on endurance running performance. Of those six studies, all have demonstrated significant improvements in running performance confirming the profound ergogenic effect of this practice (1, 6, 33, 53, 54, 59). The duration of these protocols has ranged from 19 to 30 minutes and included subjects of various fitness levels from physical education students (53) to highly trained runners (1, 59).

Arngrimsson et al. (1) investigated whether a cooling vest worn during a 38 minute warm-up would improve 5km run time in hot and humid conditions (32°C, 50% humidity). Subjects included both male and female high-level, competitive runners. Following the warm-up, T_{es} , T_{re} , mean skin, and mean body temperatures were 0.3, 0.2, 1.8 and 0.4°C lower in the vest condition. Heart rate was also reduced, averaging 11 beats per minute lower in the cooled condition. However, most of these differences were eliminated by 3.2km of the 5km run. In the precooled condition, athletes ran an average of 13 seconds faster than the control condition with no difference in improvement between sexes. Treadmill speed was fixed during the first 1.6km of the run, preventing the athletes from adopting a faster pace until later in the protocol potentially

Table 2.1: Summary of precooling studies utilizing an endurance running protocol.

Study	Precooling method	T _c reduction	Ambient conditions	Relevant results
Arngrimsson et al. ¹	Ice vest	0.5°C [†]	32°C 50%rh	5km time reduced by 13s or 1.1%
Booth et al. ⁶	Water (29-23°C)	0.7°C [†]	32°C 60%rh	Distance increased 4%, heart rate lower until min 10, increased lactic acid during 30min run.
Lee and Haymes ³³	Cold air	0.37°C [†]	27°C 50%rh	Time to exhaustion increased 17% at 82% of VO _{2max} . No change in heart rate or lactate production.
Uckert and Joch ⁵³	Ice vest	-0.54°C [‡]	31°C 50%rh	Time to exhaustion increased 2.2 min or 7% and 5.6 min or 21% compared to control and warm-up, respectively, during incremental run test.
Webster et al. ⁵⁴	Cooling vests	0.5°C [†]	37°C 50%rh	Increased run time at 95% VO _{2max} by 49s or 49% following 30 min run at 70% of VO _{2max} .
Yeargin et al. ⁵⁹	Water (14°C) Ice (5°C)	2.15°C [†] 2.33°C [†]	27°C	2 mile run time reduced by 44s or 5.7% following 90 min run and water immersion. Heart rate lower at mile 1.

T_c, core temperature; †, rectal temperature; rh, relative humidity; ‡, tympanic temperature
 - Indicates an increase in measured temperature

limiting the improvements due to precooling. An important note about this study is the velocity of the warm-up. Due to the weight of the cooling vest, the subjects ran an average of 0.8km/hour (0.5 mile/hour) slower in the precooled condition compared to the control condition. Thus, the performance improvements cannot be solely attributed to the cooling vest alone as a slower warm-up running pace would also contribute to a lower T_c .

Yeargin et al. (59) assessed whether cooling after a 90-minute run would improve performance during a two-mile run in the heat (27°C). After completing the 90-minute run, the subjects' torsos were immersed in cold water (14°C), ice water (5°C), or no water (29°C) for 12 minutes. Following cooling, T_{re} was 0.63 and 0.81°C lower in the cool water and ice water conditions compared to the no water condition. Two-mile performance time decreased with cold water immersion an average of 44 seconds or 6% compared to the control condition, however there were no other significant differences between conditions despite a lower T_c after the ice water immersion. Heart rate was reduced in the cooled conditions, but only through the first half of the race. Three of the 15 subjects were female, although no sex differences were reported.

Booth et al. (6) examined whether 60 minutes of whole body precooling would improve the distance run during a 30-minute time trial in hot and humid conditions (32°C, 60% humidity). At exercise onset, precooling reduced T_{re} by 0.7°C and increased distance covered by 304 meters or 4%. Mean heart rate was lower through minute 10 and lactate production was higher at the end of exercise following precooling. Oxygen consumption at minute 10 and 20 and sweat rate were not different between conditions. No sex differences were reported between the three female and five male subjects.

The three studies reviewed to this point have employed a time trial to monitor changes in performance. Time trials can take the form of either time to complete a given distance or distance covered in a given time. Another method to measure performance is time to exhaustion in which the athlete exercises until volitional exhaustion at a specified workload, often expressed as a percentage of VO_{2max} .

Lee and Haymes (33) investigated whether a 30-minute bout of cold air exposure would increase running time to exhaustion at 82% of VO_{2max} in normothermic conditions ($24^{\circ}C$). Rectal temperature was lowered on average by $0.37^{\circ}C$ and mean time to exhaustion increased from 22.4 to 26.2 minutes, a 17% improvement. At exercise onset, heart rate was 9 beats per minute lower and remained lower until minute 15 during the precooled condition. Oxygen consumption was also lower for the first 10 minutes of exercise. At exercise termination there were no differences in final heart rate, blood lactate, or T_{re} .

Uckert and Joch (53) compared time to exhaustion during an incremental treadmill test in the heat ($31^{\circ}C$) following a 20 minute warm-up, 20 minutes of precooling via ice vest, or without particular preparation (control). These authors found the mean time to exhaustion in the precooled trial (32.5 min) exceeded both the control (30.3 min) and the warm-up (26.9 min) conditions. The difference between the control and warm-up trials was also statistically significant ($p < .001$). Interestingly, tympanic temperature (T_{ty}) measurements indicated an increase of $0.54^{\circ}C$ following precooling instead of a decrease in T_c as would be expected. Tympanic temperature is generally regarded as a less accurate measure of T_c , and the authors stated an error of $0.2^{\circ}C$ in their T_{ty} measurements which in this author's opinion, likely confounded their results.

Webster et al. (54) assessed three different cooling vests and a control condition on time to exhaustion while running at 95% of VO_{2max} in hot conditions ($37^{\circ}C$, 50% humidity). Cooling vests were applied during a 35 minute resting and warm-up period at which point subjects removed the vests and ran for 30 minutes at 70% VO_{2max} . The time to exhaustion trial at 95% of VO_{2max} followed the 30 minute submaximal run and was increased up to 49 seconds when compared to the control condition. There were no differences between the male and female participants in heart rate, sweat rate, skin temperature, T_{re} during warm-up and exercise, or time to exhaustion. In contrast to other studies, there were no significant differences in heart rate between the cooled and control trials.

In conclusion, precooling is an effective method to improve endurance running performance as evidenced by multiple studies utilizing a variety of

precooling methods and exercise protocols. All six studies demonstrated significant improvements in running performance (1, 6, 33, 53, 54, 59) following precooling and all but one (54) demonstrated a reduction in heart rate through the initial portion of the exercise protocol. Four of the reviewed studies included female subjects (1, 6, 54, 59), however no sex differences in response to precooling were reported. A summary of these studies can be seen in Table 2.1.

Endurance Cycling Protocols

To date, eight studies have investigated the effects of precooling on endurance cycling performance (14, 25-27, 30, 32, 43, 47) and all but three (26, 27, 47) have demonstrated significant improvements in performance (Table 2.2). The duration of cycling protocols has ranged from 13 minutes to 68 minutes and have included a variety of subjects such as untrained volunteers, competitive rowers, to moderately-trained cyclists. Only one study in this group has included female subjects (47).

Cotter et al. (14) assessed whether precooling via ice vest and cold air would improve cycling endurance performance in hot conditions (35°C, 60% humidity) during a 15 minute performance trial following 20 minutes of cycling at 65% of VO_{2max} . Two precooling conditions were compared; the ice vest with the thighs kept warm and the ice vest with the thighs cooled. Both cooling conditions reduced heart rate and T_c relative to the control condition during the constant-load portion of the exercise protocol and increased power output by 17% in the performance trial. Cooling of the thighs did reduce T_c to a greater degree but did not significantly alter physiological responses or work rate. The rate of oxygen consumption did not differ between conditions during the 20 minute constant load portion of cycling.

Hessemer et al.(30) examined the influence of precooling during a 60-minute cycling time trial in normothermic conditions (18°C). A double exposure to cold air (0°C) reduced T_{es} by 0.4°C, increased mean work rate by 6.8%, mean

Table 2.2: Summary of precooling studies utilizing an endurance cycling protocol.

Study	Precooling method	T _c reduction	Ambient conditions	Relevant results
Cotter et al. ¹⁴	Ice vest + Cold air (3°C)	1.9°C (legs warm) [^] 2.8°C (legs cool) [^]	35°C 60%rh	Both conditions decreased HR relative to control during 20 min of cycling at 65% of VO _{2peak} and increased work rate (17%) during 15 min performance trial.
Gonzalez-Alonso et al. ²⁵	Water (17°C)	1.5°C*	40°C 19%rh	Increased time to exhaustion by 17 min or 37% during cycle at 60% VO _{2max} .
Hasegawa et al. ²⁶	Water (25°C)	0.3°C [†]	32°C 80%rh	Reduced heart rate, sweat loss, T _c at end of 60 min cycle at 60% of VO _{2max} . No difference in time to exhaustion at 80% VO _{2max} .
16 Hasegawa et al. ²⁷	Ice vest	No Change [†]	32°C 75%rh	Reduced heart rate, T _c , during 60 min cycle at 60% VO _{2max} . No difference in time to exhaustion at 80% VO _{2max} although sweat loss was less.
Hessemer et al. ³⁰	Cold air (0°C)	0.4°C*	18°C	Increased work rate (6.8%), VO ₂ (9.6%), and reduced sweat rate (20.3%), no change in heart rate or lactate during 60 min cycle.
Kay et al. ³²	Water (26°C)	No Change [†]	31°C 60%rh	Distance increased 0.9km (17%) during 30 min cycle with reduced sweat rate.
Olschewski and Bruck ⁴³	Cold air(5-10°C)	0.2°C*	18°C 50%rh	Increased time to exhaustion by 2.3 min or 12% and lower heart rate during incremental cycle test.

T_c, core temperature; [†], rectal temperature; *, esophageal temperature; [^], mean of core and skin temperature; rh, relative humidity

Table 2.2: Summary of precooling studies utilizing an endurance cycling protocol continued

Study	Precooling method	T_c reduction	Ambient conditions	Relevant results
Schmidt and Bruck ⁴⁷	Cold air (0°C)	1.0°C [^]	18°C	Reduced heart rate and sweat rate during incremental cycle test to exhaustion. No change in work rate, total work, or time to exhaustion.

T_c, core temperature; ^, mean of core and skin temperature; rh, relative humidity

VO_2 by 9.6%, and reduced sweat rate by 20.3%. There were no differences in heart rate or post-exercise lactate values.

Kay et al. (32) demonstrated that precooling can be an effective performance enhancer in the absence of a reduction in T_c . These authors cooled subjects so that skin temperature was reduced but not T_{re} . Following cooling, subjects increased distance cycled in 30 minutes by 0.9km, an increase of 16.5%. There were no differences in heart rate or lactate values during the exercise period.

The endurance cycling studies reviewed to this point have all employed a time trial performance measure and have demonstrated significant improvements in work rate. No changes in heart rate or lactate values have been reported, however that is not unexpected as subjects are exercising at higher work rates following precooling. In other words, after precooling subjects are accomplishing more work at similar heart rate and lactate values as in the control condition. Time-to-exhaustion trials have also been utilized to demonstrate increases in performance following a reduction in T_c .

One of the most cited improvements due to precooling, a 37% increase in time to exhaustion, resulted from a study by Gonzalez-Alonso et al. (25). Subjects cycled to exhaustion at 60% of VO_{2max} under three different T_{es} (35.9, 37.4, and 38.2°C) in intense heat (40°C, 19% humidity). Following cooling, subjects cycled a mean time of 63 minutes, an impressive 37% improvement from the control condition. In the warmed condition, subjects cycled a mere 28 minutes. Heart rate was significantly reduced post cooling during the exercise trial with the exception of heart rate at exhaustion. Lactate values did not differ at exhaustion.

Olschewski and Bruck (43) investigated whether precooling would improve cycling endurance during an incremental test to exhaustion. Workload was gradually increased to 80% of VO_{2peak} over a 20 minute interval. Thereafter, subjects cycled to exhaustion at 80% VO_{2peak} . Following precooling, time to exhaustion increased 2.3 minutes or 12% and the onset of sweating was

delayed. Heart rate was lower during most of the exercise period, however was unchanged at the point of exhaustion.

Schmidt and Bruck (47) utilized a similar precooling protocol to determine changes in cycling endurance during a stepwise test to exhaustion in which workload increased every four minutes. There were no significant differences in mean maximum work rate, peak oxygen uptake, time to exhaustion, or total work. Heart rate was lower and the onset of sweating occurred later in the precooling trial. Although there were no overall differences due to precooling, the authors did mention specific changes in the three female subjects. Time to exhaustion and total work increased in the precooled trial for all female subjects, with one demonstrating an increase in VO_{2peak} exceeding 20%. These authors did not report any effort to standardize phase of the menstrual cycle among the female volunteers.

Hasegawa et al. (26, 27) completed two studies investigating the combined effects of precooling and water ingestion on cycling endurance performance in hot conditions (32°C, 70-80% humidity). In the first study (26) untrained subjects cycled at 60% of VO_{2max} for 60 minutes under four conditions; precooled, precooled with water intake, water intake only, or control. Prior to exercise precooling reduced T_{re} 0.3°C regardless of water condition, however T_{re} at the end of 60 minutes was significantly lower (by 0.2°C) in the combined condition compared to the precooled only trial. Precooling reduced heart rate through 35 minutes of the constant-load trial while the combined condition reduced heart rate the entire 60 minutes. Following the 60 minute cycling bout, subjects cycled to exhaustion at 80% of VO_{2max} . There were no significant differences in time to exhaustion or heart rate among trials except in the combined condition in which time to exhaustion was significantly longer than any other condition.

In the second study, untrained subjects completed the same exercise protocol except the cooling was accomplished via a cooling jacket which was applied during 20 minutes of rest and during the 60 minute cycle at 60% of VO_{2max} . The four conditions were similar to the previous study; wearing a cooling

jacket, cooling jacket and water intake, water intake only, or control (27). Rectal temperature was lower after cooling until minute 35 of the 60 minute cycle and heart rates were generally lower following cooling. Time to exhaustion at 80% of VO_{2max} was significantly longer in the combined condition, but similar in the precooling only and water only conditions.

To summarize the results of precooling on endurance cycling performance, all but three (26, 27, 43) have demonstrated significant improvements in work output or time to exhaustion. Of these three studies, two have investigated a combination of precooling and water intake (26, 27) obscuring the effects of precooling alone. In these protocols, the combination of cooling and water intake did increase time to exhaustion, although cooling alone compared to other conditions did not. Clearly, cooling did contribute to an increase in performance in the combined condition, although it is difficult to determine the individual effects of water intake and precooling. In the third study not demonstrating significant improvements in cycling performance (43), the authors did note impressive differences among the female volunteers.

In all of the cycling protocols reviewed, heart rate was significantly reduced during fixed rate work or remained the same at higher rates of work output during precooling trials. Additionally, lactate values have remained unchanged at the end of time trials or at exhaustion, indicating that more work has been completed for a given level of lactate production. In light of these conclusions, precooling is an effective strategy for improving both running and cycling endurance performance in both thermoneutral and hot environments.

High-Intensity Protocols

In contrast to endurance cycling and running protocols, most investigators using shorter duration, higher intensity exercise tasks (Table 2.3) have not demonstrated performance enhancements as a result of precooling (2, 3, 12, 37, 48, 49). Only two studies (10, 36) have shown improvements in performance

Table 2.3: Summary of precooling studies utilizing a high intensity protocol

Study	Precooling method	T_c reduction	Ambient conditions	Relevant results
Bergh and Ekblom ²	Water (14°C)	1.9-2.8°C*	NR	Reduced time to exhaustion during combined arm and leg work by 36% (T _{es} = 35.8) and by 47% (T _{es} of 34.9°C)
Blomstrand et al. ³	Water (11°C)	0.2°C*	NR	Reduced time to exhaustion during cycle at mean work rate of 350 watts. Greater lactate production and later appearance of peak lactate.
Castle et al. ¹⁰	Water (18°C)	0.3°C [†]	34°C 52%rh	Ice pack treatment increased peak power output during 40 min interval cycling protocol. Muscle temperature not reduced in vest condition.
	Ice vest	0.3°C [†]		
	Ice packs	0.2°C [†]		
Cheung and Robinson ¹²	Cooling vest	0.5°C [†]	22°C 40%rh	No change in mean peak power, mean overall power, or submaximal heart rate during 30 min cycling at 50% VO _{2peak} with interspersed 10 sec Wingate tests.
Marsh and Sleivert ³⁶	Water (13°C)	0.3°C [†]	29°C 80%rh	Increased mean power of 3.3% during 70 sec cycle test. No difference in lactate production.
Mitchell et al. ³⁷	Fan+water spray	0.17°C*	38°C 40%rh	Reduced time to exhaustion (10%), lower heart rate, and no change in lactate during run to exhaustion at 100% VO _{2max} .

T_c, core temperature; †, rectal temperature; *, esophageal temperature; †, telemetry temperature; rh, relative humidity; NR, not reported

Table 2.3: Summary of precooling studies utilizing a high intensity protocol continued

Study	Precooling method	T_c reduction	Ambient conditions	Relevant results
Schniepp et al. ⁴⁸	Water (12°C)	NR	NR	Greater reduction in maximum and average power during 30 sec cycle sprint when compared to control condition.
Sleivert et al. ⁴⁹	Ice vest + air (3°C) Ice vest only	0.2 – 0.5°C [#]	33°C 60%rh	Reduced peak and mean power output during 45 sec cycle test, no difference when thighs were not cooled. Reductions more pronounced when warm-up was excluded.

T_c, core temperature; #, mean of rectal and esophageal temperature; rh, relative humidity; NR, not reported

following a reduction in T_c . Female volunteers were only included in one study (10). Exercise protocols in this section lasted a minimum of 70 seconds up to 40 minutes in duration.

Bergh and Ebklom (2) investigated the effects of four different T_{es} (38.4, 37.7, 35.8, and 34.9°C) on time to exhaustion during combined arm and leg ergometry designed to elicit 110% of VO_{2max} . Mean time to exhaustion and lactate production was reduced in all conditions when compared to normal ($T_{es} = 37.7^\circ\text{C}$). Peak VO_2 and heart rate were positively correlated with T_{es} indicating lower values in the reduced T_{es} conditions. This precooling protocol induced the greatest reduction in T_{es} reported in the literature. Hypothermia is defined as a T_c below 35°C. The mean T_{es} of the coldest condition was $34.9 \pm 0.5^\circ\text{C}$ affirming that most subjects were hypothermic, and some were well below the threshold for hypothermia.

Blomstrand et al. (3) assessed the impact of cooling on high-intensity cycling at a mean work rate of 350 watts. Three trials were compared; precooled exercise to exhaustion, thermoneutral exercise to exhaustion, and thermoneutral exercise for the same duration as in the cold exhaustion trial. Precooling resulted in a reduced time to exhaustion (2.1 compared to 1.3 minutes) and later appearance of peak blood lactate when compared to the thermoneutral trial of the same duration. Peak heart rate was also reduced in the cooled trial.

Castle et al. (10) compared three treatments intended to reduce T_c , muscle temperature, or both T_c and muscle temperature. Subjects completed a 40 minute, high-intensity cycling protocol consisting of twenty repeats of 10 seconds of rest, 5 seconds of sprinting, and 105 seconds of active recovery in hot conditions (34°C, 52% humidity). The sprint protocol was preceded by 20 minutes of cold water immersion, cooling via ice vest, ice pack application to the legs, or no cooling. Peak power output increased by 4% in the ice pack condition, however there were no other significant differences among conditions. Heart rate was lower post-immersion compared to the control condition through minute 8 of the sprint protocol. Precooling via water immersion was not a

successful performance-enhancing strategy for this particular protocol, however ice pack application did increase peak power output and reduce T_{re} by 0.2°C .

Cheung and Robinson (12) evaluated cycling sprint performance after T_c reduction with an upper body cooling jacket. Subjects cycled at 50% of $\text{VO}_{2\text{max}}$ for 30 minutes and completed ten second Wingate tests interspersed at five minute intervals. There were no differences in mean peak power or overall power output between conditions. Submaximal heart rates were similar between trials, however peak heart rate was significantly reduced after cooling. Female subjects did participate in this study, however no sex differences were noted by the authors.

Marsh and Sleivert (36) assessed performance of a 70-second Wingate cycling test with and without torso precooling via water immersion. Mean power output during the 70 seconds increased 3.3% (581 to 603 Watts) after cooling and heart rate was reduced during the warm-up prior to the cycling performance test. There were no differences in blood lactate concentration.

Mitchell et al. (37) utilized a high-intensity running protocol in the heat (38°C , 40% humidity) to examine performance after cooling with a fan and water spray combination. Time to exhaustion at 100% of $\text{VO}_{2\text{max}}$ was reduced after cooling by 10% as was heart rate. There were no differences in lactate accumulation between conditions.

A study by Schniepp et al. (48) employed a pretest, posttest design to determine the effects of cold water immersion on 30 second Wingate cycling performance. Subjects performed one 30 second Wingate, followed by either immersion at 15°C water or sitting at room temperature. Subjects then performed a second Wingate test. Maximum and mean power declined during the second test for both conditions, however declines post cooling were greater (13.7 versus 4.7% for peak power and 9.5 versus 2.3% for mean power). Both maximum and mean heart rates were reduced compared to the control condition.

Sleivert et al. (49) published data examining 45-second sprint cycling performance from the same study as Cotter et al. (14). Cooling was applied via ice vest and cold air (3°C) and the thighs were either cooled or kept warm. There

were no differences in either peak or mean power after torso-only cooling (legs were warm), however, both variables were reduced (by 7.6 and 7.7% respectively compared to control) when both the torso and thighs were cooled. Additionally, these researchers sought to determine the effect of a six minute warm-up on sprint performance under the two cooling conditions. Even when a warm-up was performed, peak and mean power output were reduced (by 3.4 and 4.1% respectively compared to control) when both the torso and thighs were cooled. Heart rate was lower in the torso and thigh cooling condition both prior to and during the sprint cycle test.

To summarize the results from high-intensity protocols, precooling does not generally improve performance. Most studies have demonstrated significant decrements in performance and only two studies have demonstrated small, but significant improvements in cycling power (10, 36). In general, studies measuring lactate production have found no difference between conditions suggesting a similar lactate production with lower rates of power output post-cooling. As an exception, Marsh and Sleivert (36) also found no difference in lactate production between trials, however they did demonstrate a 3.3% increase in power output with cooling. In this case, more work was accomplished with the same lactate production.

Interestingly, heart rate was significantly reduced in all high-intensity studies, however performance was also significantly reduced. If the primary mechanism for performance improvement due to precooling is a reduction in thermal strain and a greater blood flow to the working muscles, which is generally supported by endurance studies, then high-intensity performance should be improved as well. The results of these studies clearly demonstrate lower mean and peak heart rates, however performance is not improved and is most commonly decreased following cooling. Why would both heart rate and performance be reduced after cooling?

Perhaps the decline in heart rate is not due solely to reductions in thermal strain, but rather a myriad of physiological responses to cold exposure. In this scenario, a greater portion of blood flow may not be circulating to the working

musculature explaining the lack of performance improvement. Another possibility is that thermal strain is reduced as suggested by a reduction in heart rate, but other factors that influence high-intensity performance, such as rate of anaerobic metabolism, may be negatively impacted ultimately reducing high-intensity performance. Regardless of why performance is reduced following cooling, the results of these studies do not support the practice of precooling prior to high-intensity competition.

Non-Performance Protocols

In effort to eliminate some of the drawbacks of performance-based protocols, such as different work rates between trials and the impracticality of time to exhaustion protocols, several researchers have designed studies to hold the exercise task constant (Table 2.4) and measure changes in physiological variables such as heart rate, VO_2 , sweat rate, and muscle metabolite content (4, 7, 18, 21, 22, 58). In most cases, heart rate is the only variable demonstrated to change after precooling.

Bolster et al. (4) investigated the effects of a reduced T_c on a simulated triathlon in the laboratory. Subjects swam for 15 minutes at 82% of $\text{VO}_{2\text{max}}$ and then cycled at 75% of $\text{VO}_{2\text{max}}$ for 45 minutes. Following a T_{re} reduction of 0.5°C there no significant differences in heart rate, VO_2 , or sweat rate. The only significant difference was greater body heat storage in the precooling condition.

Booth et al. (7) evaluated changes in muscle metabolism following whole-body water immersion. Subjects cycled at 60% of $\text{VO}_{2\text{peak}}$ for 35 minutes following cooling or immersion in thermoneutral water. Despite a fairly large decrease in T_{es} (mean decrease 0.6°C over 35 minutes) there were no significant differences in resting ATP, creatine phosphate, lactate, glycogen, or triglyceride content post-exercise. Heart rate tended to be lower throughout exercise in the precooling trial.

Daanen et al. (18) assessed the effects of whole-body cooling, lower-body cooling, upper-body cooling, and no cooling on 40 minutes of cycling at 60% of

Table 2.4: Summary of precooling studies utilizing a non-performance protocol

Study	Precooling method	T _c reduction	Ambient conditions	Relevant results
Bolster et al. ⁴	Water (25.6°C)	0.5°C [†]	26.6°C 60%rh	No change in heart rate, VO ₂ , or sweat rate during 15 min of swimming at 82% VO _{2max} and cycling 45 min at 75% VO _{2peak} .
Booth et al. ⁷	Water (29-24°C)	0.8°C*	35°C 50%rh	No change in VO ₂ , muscle glycogen, triglyceride, ATP, creatine phosphate, or lactate content following 35 min cycle at 60% VO _{2peak} .
Daanen et al. ¹⁸	Water suit	0.07 – 0.12°C ⁺	30°C 70%rh	No change in gross efficiency, lower sweat and heart rate during 40 min cycle at 60% VO _{2max} .
Drust et al. ²¹	Shower (26°C)	0.6°C [†]	20°C 70%rh 26°C 61%rh	No change in VO ₂ , heart rate, minute ventilation, plasma lactate, or glucose during 90 minute soccer-specific running protocol.
Folland et al. ²²	Water (21.0°C)	No change [†]	NR	No change in VO ₂ , lower heart rate, shorter stride length, and higher stride frequency during 10 min run at 70% VO _{2peak} .
Wilson et al. ⁵⁸	Water (17.7°C)	0.23°C [†]	21.3°C	No change in mechanical efficiency or metabolic rate but reduced sweat rate and onset of sweating during 60 min cycle at 60% of VO _{2max} .

T_c, core temperature; †, rectal temperature; *, esophageal temperature; +, telemetry temperature; rh, relative humidity; NR, not reported

VO_{2max} in the heat (30°C, 70% humidity). Gross efficiency, or oxygen cost of the workload, did not differ significantly between conditions. All cooling trials reduced heart rate relative to the control trial and there were no differences in respiratory exchange ratio.

Drust et al. (21) utilized a 90-minute soccer-specific intermittent treadmill running protocol to determine the effects of precooling in normal ambient conditions (20°C). Additionally, subjects completed the protocol without precooling in warm conditions (26°C). The researchers found no significant differences in VO_2 , heart rate, minute ventilation, rating of perceived exertion, or plasma lactate, glucose, or free fatty acid concentration. These results do not suggest a beneficial effect of precooling for soccer performance.

Wilson et al. (58) compared the effects of cold (18°C) and thermoneutral (35°C) water immersion on metabolic variables during a 60-minute cycle at 60% of VO_{2max} . No significant differences were noted in VO_2 , mechanical efficiency, or rating of perceived exertion. Heart rate was reduced, but only through minute 5 of the exercise protocol. Onset of sweating was delayed by 19.62 minutes and mean sweat rate was also reduced compared to the control condition.

In the study most closely related to the current investigation, Folland et al. (22) examined changes in RE and stride parameters following leg immersion in cold (21.0°C), thermoneutral (34.6°C), or hot (41.8°C) water. Following immersion, subjects completed a 10-minute treadmill run at a workload corresponding to 70% of VO_{2max} . Mean oxygen cost and minute ventilation were not different between trials whereas exercise heart rate increased with increasing water temperature. While the metabolic variables remained unchanged after the temperature manipulation, stride parameters were altered post cooling. Stride length decreased and stride frequency increased in the cold condition compared to the thermoneutral and hot condition.

To summarize the non-performance protocols, most studies did not find significant differences in variables of interest, such as lactate or mechanical efficiency, following cooling. There were no changes in metabolite concentration and a reduction in heart rate continued to be a consistent finding. Of most

interest, stride parameters were significantly altered after cooling, however oxygen uptake was not altered in any study measuring this variable.

The results of all studies investigating the performance-enhancing effects of precooling support the use of this practice with endurance events, such as distance running and cycling, but not for high-intensity exercise, such as cycling intervals or maximal running. The mechanism underlying these improvements remains unknown. Currently, most researchers attribute performance improvements to a reduction in thermal strain as evidenced by a reduced heart rate. A reduction in heart rate has been the most consistent finding in the literature. However, while this is a plausible explanation for improvements in endurance performance, high-intensity exercise is not improved, and in most cases declines, post-cooling in spite of a lowered heart rate. Data from non-performance protocols have not elucidated any other mechanism to explain the enhancement during endurance performance.

It has been suggested that precooling may only be effective in hot and humid conditions. Of the endurance running protocols reviewed, two (33, 59) were completed in moderately warm conditions (27°C) and the remaining protocols (1, 6, 53, 54) occurred in hot and humid conditions (mean temperature = 33°C, 50% humidity). However, the greatest performance gains were realized in the protocols conducted in moderate heat (33, 59), not in hot and humid conditions. Likewise in the endurance cycling protocols, tremendous performance improvements were demonstrated in hot and humid conditions (14, 25, 32) as well as in thermoneutral conditions (30, 43). Of the three cycling protocols that did not demonstrate increases in performance, two were conducted in hot and humid environments (26, 27) with the remaining protocol occurring in normal ambient conditions (47).

As for the high-intensity exercise tasks, three studies failed to report environmental conditions (2, 3, 48), three studies were conducted in hot conditions (10, 37, 49), and two studies were completed in thermoneutral or moderately-warm conditions (12, 36). Of the two investigations demonstrating significant improvements in performance, one study was performed in hot

conditions (10). However, the intervention associated with the improvements utilized ice packs and reduced T_{re} by 0.2°C in contrast to the other cooling interventions, water immersion and ice vest application, which reduced T_{re} to a greater degree (0.3°C) and were not associated with performance improvements. The second study to demonstrate enhancements in performance occurred in moderately warm conditions (29°C).

Two of the non-performance experiments were conducted above normal ambient conditions (7, 18). However, neither the studies conducted in the heat nor those conducted in normal conditions demonstrated any significant change in variables of interest with the exception of heart rate, which tended to be lower regardless of ambient conditions. In the Folland et al. study (22), in which RE was the variable of interest, ambient conditions were not reported.

Of the 28 studies included in this review, only 12 were conducted in hot conditions, seven of which produced significant changes in performance or key variables following cooling. Nine studies were completed in normal ambient conditions, three of which produced significant improvements in performance. Thus, at this point in time, previous work does not support the contention that precooling is only effective in hot and humid conditions.

Running Economy

Endurance performance is determined by a number of physiological variables including maximal oxygen consumption ($\text{VO}_{2\text{max}}$), lactate threshold, and running economy (RE). Among a cross-section of runners with varying abilities, those athletes with the highest $\text{VO}_{2\text{max}}$ values will be the fastest runners. However, among a group of highly trained, elite runners very little variation exists in $\text{VO}_{2\text{max}}$ values indicating that this variable alone does not determine performance or race outcomes. Other variables, such as lactate threshold and running velocity at the lactate threshold, become important determinants of endurance running performance among highly-trained athletes.

Running economy is defined as the oxygen cost of running at a constant submaximal workload. An athlete is considered to be more “economical” if they

consume less oxygen at a specific workload than another athlete. For example, if athlete A consumes $43 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ to run at 9.5 miles per hour and athlete B consumes $48 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ to run the same speed, then athlete A is considered more economical. But how does this variable determine the outcome of a race? In the previous example, if both athletes had identical $\text{VO}_{2\text{max}}$ values and identical lactate thresholds ($50 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), then athlete B is running at a higher percentage of $\text{VO}_{2\text{max}}$ and closer to his lactate threshold than athlete A. Athlete B can only increase his pace slightly before lactate begins to accumulate in the bloodstream leading to the onset of fatigue. Athlete A, on the other hand, can increase his pace considerably before reaching his lactate threshold. Thus, athlete A can maintain a much higher running velocity and ultimately finish a race faster than athlete B.

Running Economy and Performance

As previously mentioned, among a group of runners heterogeneous in running ability, $\text{VO}_{2\text{max}}$ is significantly correlated with running performance. However, as a group of runners becomes more homogenous with respect to $\text{VO}_{2\text{max}}$ and running performance, running economy can explain much more of the variation in performance times.

Conley and Krahenbuhl (13) measured VO_2 at three velocities (9.0, 10.0, and 11.0 mph) in elite male runners (mean $\text{VO}_{2\text{max}} = 71.7 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and recorded 10km race performance (mean 10km time = 32.1 minutes). These authors found no significant correlation between $\text{VO}_{2\text{max}}$ and performance in the 10km run. However, there was a significant correlation between VO_2 at all three testing speeds and 10km time. In this study, RE accounted for approximately 65% of the variation in 10km performance.

Williams and Cavanagh (55) determined VO_2 at 8.0 mph in actively training runners, a subset of which also completed a 10km race (mean 10km time = 35.15). These authors did not find significant correlations between $\text{VO}_{2\text{max}}$ and 10km time, between RE and $\text{VO}_{2\text{max}}$, or between RE and 10km time. A number of biomechanical variables, such as ground reaction forces and vertical

oscillation, were also recorded. No single variable or subset of variables was able to fully explain differences in RE among subjects. The participants in this study were on average less successful and demonstrated greater heterogeneity in VO_{2max} and 10km time than the previous study.

Morgan et al. (38) measured VO_2 at four velocities (8.6, 9.3, 10.0, and 10.9 mph) in a group of male runners homogenous in both VO_{2max} values ($64.8 \pm 2.1 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and 10km time ($32.29 \pm 1.27 \text{ min}$). These authors did not find a significant correlation between VO_{2max} and 10km, but did find a significant correlation between RE and 10km.

Thus, for runners to reach a certain level of accomplishment they are required to have a high VO_{2max} and to produce fast performance times. However, those athletes with the best economy will continue to win races whereas those with lower economy will always finish slower regardless of their aerobic capacity.

Factors That Influence Running Economy

Running economy is influenced by a number of variables such as sex, training status, temperature, flexibility, and phase of the menstrual cycle. Some of these variables are modifiable, such as training status, flexibility, and temperature, while others are not. In general, highly-trained males demonstrate the most economical running whereas untrained subjects and female subjects run less economically.

Training Status

Bransford and Howley (8) compared RE among trained male and female distance runners and untrained male and female subjects. These authors found that trained male runners had a significantly lower oxygen cost than any other group at any measured speed. Trained female subjects also had a lower oxygen cost than untrained female subjects. However, there was no significant difference between trained female runners and untrained male runners. Thus, trained athletes utilize less oxygen to run at the same workload than their

untrained counterparts and female subjects are less economical than male subjects even when highly-trained.

Sex

Daniels and Daniels (19) measured RE among male and female subjects training for the U.S. Olympic Trials, most of which competed in the trials, and five of which went on to win Olympic medals. Running economy was determined at a number of speeds for each sex and included five common speeds. Men consumed less oxygen than women at all common absolute velocities. When men and women of equal VO_{2max} were compared, the male subjects were significantly more economical. In comparisons of male and female runners with equal RE, the male subjects had greater VO_{2max} values and higher velocities at VO_{2max} . Thus, even among male and female subjects with equal RE, male runners are at a significant aerobic advantage.

Temperature

MacDougall et al. (34) measured a variety of exercise variables including VO_2 , heart rate, and ventilation while subjects ran to exhaustion at approximately 70% of VO_{2max} under three conditions: while wearing a jacket perfused with cool water, warm water, and no water. These authors found in the cooling condition, time to exhaustion increased by 15.75 min when compared to the control condition, and increased by 42.5 min when compared to the warm water condition. Both VO_2 and heart rate were lower in the cool water condition when compared to both the normal and warm water conditions. While this study did not precool their subjects per se, the cooling condition did delay the rise in T_c , VO_2 , and heart rate during exercise in normal conditions (23°C).

Flexibility

Lower-body flexibility has been negatively associated with running economy so that individuals with reduced flexibility tend to be more economical runners. Studies in this area have included a variety of participants, from elite

runners (16, 31) to recreationally-active individuals (23, 24, 42). Each study that compared flexibility to RE found a significant correlation between these variables indicating that the least flexible subjects demonstrate the lowest oxygen cost of walking, jogging, and/or running.

Jones (31) compared RE at three submaximal speeds to sit and reach score in International distance runners. This author found a significant positive correlation between sit and reach score and the oxygen cost of running at all speeds. Oxygen cost at 16.0 km/hour (10.0 mph) averaged $50.6 \pm 3.7 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ with a range from 44.2 to 57.1 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ representing a variation of 25%. In this study, 46% of the variability in RE was explained by differences in flexibility. There was no significant correlation between $\text{VO}_{2\text{max}}$ and RE and a correlation between RE and performance was not reported.

Craib et al. (16) measured lower limb and trunk flexibility and RE at approximately 9.25 mph in highly trained male distance runners (mean $\text{VO}_{2\text{max}} = 67.4 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, mean 10km time = 34.2 minutes). These authors provided 60 minutes of treadmill accommodation prior to the RE measurements. Mean oxygen cost (\pm standard error) at the test speed was $45.4 \pm 0.6 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ with a range from 39.8 to 49.7 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. This indicated a variation of 22% in RE among this subject group. Significant correlations were found between dorsiflexion and standing hip rotation and the oxygen cost of running, demonstrating that the least flexible runners were the most economical. However, sit and reach score was not significantly correlated to oxygen cost as in the previous study (31). In this study, 47% of the variation in RE was explained by variance in flexibility. Correlations between $\text{VO}_{2\text{max}}$ and RE and 10km performance and RE were not reported.

Gleim et al. (23) examined exercise economy at six speeds from a slow walk (2.0 mph) up to a moderate run (7.0 mph) and measured flexibility on 11 tests of trunk and lower body flexibility. The 100 physically active subjects were split into thirds by mean flexibility score. At speeds of 4.0 mph and greater, the least flexible group consumed significantly less oxygen than the most flexible group (mean difference = 9%). Lower body flexibility, as assessed by toe touch

ability, was significantly associated with oxygen cost so that the least flexible group consumed less oxygen than the more flexible group.

Two studies have investigated the influence of stretching on subsequent RE. Godges et al. (24) utilized two stretching interventions to determine changes in hip range of motion (ROM) and oxygen cost at 40, 60, and 80% of VO_{2max} . Following both of the stretching routines, hip flexion and extension increased. When compared to pretest values, oxygen cost was lowered at all exercise intensities following static stretching but only at the moderate intensity following proprioceptive neuromuscular facilitation. However, these authors did not include a control day in which no stretching occurred between oxygen cost measurements. Thus, oxygen cost may be reduced in the post test for other reasons. For example, adequate treadmill accommodation was not provided so that an apparent improvement in economy may be reflective of adjustment to the treadmill and oxygen measurement devices.

In a study by Nelson et al. (42), participants completed a 10-week stretching program to determine changes in RE at 5.0 and 6.0 mph for female and male subjects, respectively. Sit and reach score increased by a mean of 9% in the stretch group, whereas there was no change in the control group. However, RE during a 10 minute treadmill run did not change for either group.

Authors from the latter two investigations utilized stretching interventions to determine any changes in RE. While acute stretching was linked to an improved RE in one study, chronic stretching did not change RE in the other. It is unknown whether a significant correlation existed between RE values and flexibility of the subjects either before or following the stretching treatments. In addition, both subject groups were recreational active individuals as opposed to highly trained runners included in the studies by Jones (31) and Craib (16).

In summary, all studies reporting correlations between RE and flexibility have found these associations to be significant and furthermore, to explain almost half of the variance in RE measures. Additionally, significant correlations between RE and flexibility were found among a variety of treadmill speeds (from 2.0 mph up to 10.0 mph) and among a variety of subjects (from physically active

to highly trained, elite athletes). However, interventions to modify flexibility have not produced strong evidence that RE can then be modified as a result.

Menstrual Cycle Phase

Running economy is influenced by a number of variables, and sex is no exception. All studies comparing athletes of different sexes demonstrate that women are at an aerobic disadvantage compared to men. Men demonstrate higher VO_{2max} values, higher velocities at VO_{2max} , and better economy while running. In addition, exercise variables such as heart rate, T_c , VO_2 , and RE demonstrate cyclic changes during the menstrual cycle. The two prominent phases are the follicular phase, which starts with the onset of menses and continues until ovulation of the mature ovum lasting anywhere from 10 to 16 days. The luteal phase follows ovulation and lasts roughly eight days. If the egg is not fertilized during this time, the expanded uterine lining is shed during menses. Heart rate, T_c , and VO_2 are high, whereas RE is low, during the luteal phase. The reverse is true, lower heart rate, T_c , VO_2 , and better RE, during the follicular phase. Thus, exercise performance is likely to be higher during the follicular phase.

Coyne et al. (15) continuously monitored T_c in women during 11 menstrual cycles using radio telemetry. T_c was collected each minute for 14 days during each cycle. These authors found that the lowest mean T_c value occurred during the preovulatory phase ($36.91 \pm 0.11^\circ\text{C}$), followed by the follicular phase ($37.08 \pm 0.13^\circ\text{C}$), and peaked during the luteal phase ($37.39 \pm 0.13^\circ\text{C}$). Estrogen, which surges prior to ovulation, is associated with lower T_c whereas progesterone reverses this effect (50). Thus, core temperature is lower during the follicular and preovulatory phases compared to the luteal phase.

Hessemer and Bruck (29) had female subjects undergo intense cycling exercise at night, when T_c differences are maximized, during both the luteal phase and the early follicular phase. During exercise in the luteal phase, these authors found elevations in T_c (mean increase 0.5°C), heart rate (mean increase 7 bpm), and VO_2 (mean increase 0.11 L/min) compared to the follicular phase.

In addition, elevated thresholds for sweating and vasodilation were demonstrated during the luteal phase, which may account for the elevated T_c during this phase.

Williams (56) assessed minute ventilation and RE in eight eumenorrheic moderately-trained runners at two exercise intensities, 55% of VO_{2max} and 80% of VO_{2max} and at rest on five days distributed throughout the menstrual cycle. This author found a significant elevation in ventilation during rest and exercise in the mid-luteal phase compared to the early follicular phase. In addition, RE was significantly worse during the mid-luteal phase compared to the early follicular phase at 80% of VO_{2max} , however there were no significant differences at 55% of VO_{2max} . Therefore, greater ventilatory drive increases the oxygen demand of running during the mid-luteal phase when compared to the early follicular phase of the menstrual cycle.

In conclusion, exercise variables such as T_c , heart rate, ventilation, VO_2 , and oxygen cost of running are influenced by phases of the menstrual cycle. During the luteal phase, these variables are elevated and likely to reduce endurance exercise performance whereas these variables are significantly lower during the follicular phase. It is well known that elite female runners are often amenorrheic (56), and differences between phases are likely to be dampened as a result. In addition, progesterone reverses the temperature lowering effect of estrogen (50), thus women using hormonal contraceptive methods will demonstrate different patterns of change when compared those who do not.

Proper Measurement of Running Economy

Running economy is the oxygen consumed at a specific workload, thus proper measurement of oxygen consumption is necessary to determine accurate values of RE. Even under well-controlled circumstances, oxygen consumption will fluctuate minute-to-minute and day-to-day. Several authors have determined that most daily variation in RE is accounted for in the first two days of treadmill running, and as a result, suggest providing subjects with 30 – 60 minutes of treadmill accommodation prior to RE measurement. Additionally, untrained

subjects tend to demonstrate the most variability whereas highly trained runners demonstrate the least variability.

Williams et al. (57) assessed RE in 10 moderately-trained male runners five days per week for four weeks to determine the within-subject variability of this measure. Runners were tested at three treadmill speeds (6.0, 7.0, and 8.0 mph) for six minutes at each speed following 60 minutes of treadmill accommodation. These authors determined that approximately 90% of individual variation is accounted for within the first two days of RE testing. Furthermore, RE was a stable measure throughout the four weeks of testing despite continued run training by the subjects. Thus, intra-individual variation in RE is relatively low, and a majority of which can be accounted for within two testing sessions.

Morgan et al. (40) performed a similar study in which highly-trained male and female runners completed RE testing five days per week for four weeks. In this study, no efforts were made to control for either training or racing during the testing period to determine if RE is less stable than under controlled conditions. Following 60 minutes of treadmill accommodation, these authors found that between 97 and 99% of the variation in RE could be captured in the first two testing sessions.

Morgan et al. (41) monitored both RE and a number of running mechanic variables in trained male runners to determine both daily and stride-to-stride variation. Following 30 – 60 minutes of treadmill accommodation, these authors found high day-to-day reliability for RE with a mean variation from day 1 to day 2 of 1.32%. Additionally, of the 22 mechanical variables monitored, no stride-to-stride differences and only three day-to-day differences (increased peak velocity of the ankle joint, step length, and swing time) occurred from day 1 to day 2. Thus, these authors determined that following accommodation, both RE and running mechanics are stable measures.

In summary, RE is a stable measure in trained runners following 30 – 60 minutes of treadmill accommodation. Within-individual variation is lowest among highly trained runners, and increases only slightly as running ability is reduced. Regular training and racing do not appear to influence daily RE in trained

runners. Thus, RE is a consistent variable despite fluctuations in training and day-to-day changes in running mechanics.

In conclusion, RE is defined as the oxygen cost of running at a specific speed. Even among athletes with similar VO_{2max} values and performance times, RE can vary up to 25% for athletes running at the same workload (31). Clearly, the most economical runner, or the athlete consuming the least amount of oxygen, has an advantage during endurance racing. Running economy is influenced by a number of variables. Trained subjects are more economical than untrained subjects and male runners are more economical than female runners of comparable training status. Additionally, female subjects can be more or less economical depending on phase of the menstrual cycle. Flexibility is also linked to RE so that subjects with the least flexibility demonstrate the best economy. Despite the variety of factors that can influence this variable, RE is a stable measure within an individual following treadmill accommodation.

Precooling and Running Economy

How might precooling influence RE? Precooling has been demonstrated to be a potent enhancer of endurance performance, however no specific mechanisms to explain these improvements in performance have been determined. Heart rate is often reduced during and following precooling protocols when compared to the control, even in studies in which performance does not improve (26, 27, 37, 47). Likewise, increases in time to exhaustion at a similar workload have been reported without a significant decrease in heart rate (33, 43). Thus, changes in heart rate cannot fully explain the ergogenic effect of precooling.

Attempts to determine the metabolic consequences of this practice, while keeping the exercise workload constant, have failed to provide additional insight into the mechanisms responsible for these dramatic improvements. Exercise economy has been the primary variable of interest in two studies to date (18, 22) and neither study demonstrated a significant difference in oxygen consumption following cooling. However, in the investigation measuring RE (22), treadmill

accommodation trials were not provided to the subjects. Thus, RE was likely to improve during consecutive trials regardless of which experimental trial (cooling, warming, or neutral water immersion) was being completed potentially blurring the effect of precooling on oxygen uptake. Additionally, RE was monitored for only 10 minutes, and differences in RE were demonstrated after 15 minutes of running in the MacDougall et al. study (34) although these subjects were also not treadmill accommodated. Thus, to determine the changes in VO_2 in response to precooling, subjects should be treadmill accommodated and RE should be monitored for a greater duration than 10 minutes. Additionally, to limit within-individual variability, highly-trained subjects are the ideal subject group.

As phases of the menstrual cycle have been known to influence key metabolic variables such as heart rate, VO_2 , and T_c , phase of the menstrual cycle and the use of exogenous hormones must be standardized in female subjects. During the early follicular phase, and the placebo week for oral contraceptive users, heart rate, VO_2 , and T_c are lower and RE is higher than compared to the luteal phase. This phase is also quickly determined as women know when they will begin taking their placebo tablets or when they expect to begin their next cycle. Thus, for this investigation, all female subjects will complete the experimental trials during the early follicular phase. While it is outside the scope of this investigation, precooling may be more or less effective for female athletes depending on phase of the menstrual cycle.

A fairly strong association between flexibility and RE has been determined in previous studies (16, 23, 31). In addition to VO_2 assessment, flexibility will also be monitored before and after the precooling procedure as well as before and after the control condition. Thus, the correlation between flexibility and RE will be determined in this subject group. Additionally, if precooling is associated with a reduction in flexibility and an increase in RE, then the change in flexibility may account for some improvement in RE.

The purpose of this study is to monitor changes in flexibility and RE as a result of moderate precooling. Intra-individual variability will be minimized by providing two treadmill accommodation trials as well as recruiting highly-trained

runners. In addition, menstrual cycle phase of the female subjects will be standardized to the early follicular phase. Finally, the RE protocol will be 20 minutes in duration to allow differences in $\dot{V}O_2$ to become apparent.

Chapter III

Methods

The purpose of this chapter is to describe the procedures employed in the investigation. This study employed a crossover design in which each subject participated in both the experimental and control conditions. Subjects included highly trained male and female runners between the ages of 20 and 39 years of age. We screened potential subjects for disease and other contraindications for exercise and ingestion of a temperature sensor. Each subject completed four testing sessions. The first two sessions served as accommodation trials to allow the subjects to adjust their running style to the laboratory treadmill and to accommodate to the mouthpiece utilized for measurement of oxygen consumption. In addition, body composition and VO_{2max} were assessed during these visits. Although it was the goal of the investigator to have the subjects complete the precooling and control trials in randomized balanced order, this was not achieved due to water temperature irregularities. Of the eight male subjects, four subjects completed the precooling trial first whereas the remaining four completed the control trial. However, only one of the seven female subjects completed the precooling trial first while the remaining six female subjects completed the control trial first. Investigators performed all testing sessions in the Exercise Physiology Laboratory at the University of Kentucky in Lexington, Kentucky. Data were collected by the same investigator during all testing sessions.

Study Population

Subjects recruited for the investigation included highly trained male and female runners between the ages of 20 and 39 years. To insure that the runners were capable of running on the treadmill at the predetermined pace, each subject was required to provide race results indicating they had met specific predetermined criterion times. In this study, males were required to have run a ten

kilometer race in 39 minutes or better and females were required to have run the same distance in 45 minutes or better. In some cases, 10km time was estimated from half marathon times or for one subject, from a one mile time.

Subjects were healthy as defined as free of diagnosed cardiovascular and respiratory disease. Additionally, volunteers were non-smokers, currently undertaking run training a minimum of three days per week for at least three months, and free of lower-body injury that would impair running performance. The manufacturer of the ingestible temperature sensor specified additional exclusions including bodyweight below 80 pounds, history or presence of any gastrointestinal disorder, disease, or surgery, and implantation of any electrical device such as a pacemaker. Progesterone from endogenous sources and from contraceptive use has been demonstrated to increase core temperature and oxygen consumption (50). Thus, any female subjects using implanted contraceptive devices that released progesterone or taking progesterone oral contraceptives continuously were excluded from the study.

Each subject completed a Health History Questionnaire to identify exclusionary factors indicating the aforementioned conditions. Eighteen subjects granted signed consent to participate after review of the consent approved by the Institutional Review Board of the University of Kentucky. All eighteen subjects completed the first testing session. One male subject was excluded during the course of testing session two due to an inability to maintain an appropriate running pace during the RE trial. Another male subject was excluded due to elevated blood pressure while precooling. A female subject was excluded after completion of three testing sessions due to slow intestinal motility and a lengthy duration to pass the ingestible temperature sensor. Another female subject chose to discontinue testing after completion of session one.

Measurement Sessions

Initial Meeting and Treadmill Accommodation Session #1

For the first meeting, potential subjects reported to the Exercise Physiology Laboratory at the University of Kentucky. Upon entering the laboratory, the study procedures were fully explained to the subject and they were asked to complete the Informed Consent form (Appendix 1). Following signing of the consent form, subjects completed the Physical Activity Readiness Questionnaire (PAR-Q, Appendix 2) and a Health, Training, and Injury History Questionnaire (Appendix 3). Evidence of meeting the performance criterion was obtained by the investigator. Although flyers and initial emails and phone conversations included descriptions of the automatic exclusion criteria for the study, the PAR-Q and Health, Training, and Injury History Questionnaire verified that subjects did not meet any of these criteria. The latter questionnaire included inquiries regarding training status, lower body injuries, presence of disease, past race results, and upcoming racing plans. Female subjects answered additional questions regarding menstrual cycle status and use of hormonal contraceptives.

Once the subject had been invited to participate, the subject was fitted with a heart rate monitor (Vantage XL, Polar Electro Oy, Finland) and weighed using an American Digital Scale (Lexington, KY). A blood pressure screen (via auscultation) was performed to ensure a normal response to exercise. Blood pressure was measured at rest and while the subject walked at 2.0 and 2.5 miles per hour on the treadmill. No subjects were excluded based on the initial blood pressure screen. Study participants then completed the first treadmill accommodation session allowing the individual to adapt his or her running style to the motorized treadmill (Trotter Model 685, Medway, MA) and to adjust to the mouthpiece used for RE measurement.

The treadmill accommodation session consisted of a single 23-minute treadmill workload consisting of a one minute rest while standing on the treadmill, one minute walking at 3.5 mph at 0% grade, one minute acceleration to the sex-specific running speed, and twenty minutes at the sex-specific speed (Table 3.1).

Table 3.1: Treadmill workloads

	Male	Female
Workload	8.6 mph / 0% grade	8.0 mph / 0% grade

mph- miles per hour

During the treadmill running, oxygen consumption was measured to determine RE. All measurements of oxygen consumption were determined using a Physiodyne Max II metabolic cart (New York, NY). Prior to each testing session, the oxygen and carbon dioxide sensors were calibrated for concentration using standard gases and the pneumotach was calibrated for flow using a three liter calibration syringe (Hans Rudolph, Kansas City, MO). Ambient conditions such as temperature, barometric pressure, and humidity were measured and entered into the Physiodyne software.

To measure oxygen consumption, the subjects were required to run while breathing through a mouthpiece linked to a two-way valve and to two plastic hoses. A nose clip was worn to prevent air exchange through the nose. In this setup, all inhaled air passed through the pneumotach, one plastic hose, and one of the valves before reaching the subject's mouth. Exhaled air then passed through the remaining valve, through the other plastic tube, and into the mixing chamber of the metabolic cart. Air samples from the mixing chamber were analyzed for carbon dioxide and oxygen concentration by the gas analyzers. All data from the metabolic cart were reported in one-minute averages.

Following the first treadmill accommodation sessions, body composition was assessed via hydrostatic weighing. Subjects changed into a swimsuit and height was determined using a wall-mounted stadiometer (Seca, Hanover, MD). Bodyweight was recorded again to account for differences in attire and sweat losses from the treadmill run. Once seated inside the tank, subjects submerged themselves at maximum exhalation to determine underwater weight. Subjects completed between six and ten trials, until the highest repeatable value was determined. Body density and body fat percentage was then calculated using the Siri Equation (9).

Treadmill Accommodation Session #2

Study participants returned to the Exercise Physiology lab within five days of the first visit to complete another treadmill accommodation session. Subjects completed the identical protocol as described in the previous section. Following the second treadmill accommodation session and a fifteen minute rest, each subject completed a graded exercise test to exhaustion to determine maximal oxygen consumption, a measure of aerobic fitness. A heart rate monitor was fitted to the subject as well as the mouthpiece and nose clip worn for RE measurement. The graded exercise test began with one minute of standing, one minute of walking at 3.5 miles per hour and a one minute of acceleration to the testing velocity. Testing velocity was determined with input from the subject regarding an appropriately challenging workload at which the subject could complete several stages at an incline. Following the acceleration minute, subjects ran for two minutes at 0% grade at the determined testing velocity. In two-minute intervals, treadmill grade was increased 2% until the subject was unable to continue. Ratings of perceived exertion were recorded during the last twenty seconds of each stage. Once the subject reached volitional exhaustion, treadmill speed and then grade were reduced to allow the subject to recover.

Precooling Trial

Within one week of completion of treadmill accommodation, each subject returned the laboratory to complete the experimental and control conditions. The order of conditions was randomized and balanced among the male subjects so that half completed the precooling trial first and the remaining subjects completed the control trial first. For the female subjects, only one completed the precooling trial first while the remaining six completed the control trial first. Warm weather during the early summer months elevated incoming water temperature, far exceeding the temperature for the precooling trial. Several precooling trials were canceled and the subjects completed the control trial instead. Precooling trials were rescheduled using water that had cooled to room temperature overnight.

Significant elevations in T_c , heart rate, and oxygen consumption have been found during the luteal phase of the menstrual cycle (29) and during progesterone administration (50). Thus, female subjects completed both the precooling and control trials during the follicular phase of the menstrual cycle. All female were currently taking oral contraceptives and thus completed the experimental trials during the placebo week.

Between two and four hours prior to arrival to the laboratory, subjects ingested a single-use temperature sensor (CorTemp, Palmetto, FL) utilized to record T_c . Upon arrival to the laboratory, the investigator used the CorTemp handheld recorder to confirm the presence and activation of the temperature sensor. Subjects then changed into attire to be worn while precooling (either swimsuit or running shorts), fitted themselves with the heart monitor chest band, and were weighed. Lower body flexibility was assessed via the sit and reach test (Acuflex I, Novel Prod. Inc, Rockton, IL) by which each subject reaches towards their toes as far as possible. The investigator held the subjects' knees to prevent bending during the test. Subjects completed three trials, the highest of which was utilized for data analysis. Following the sit and reach test, subjects entered the hydrostatic weighing tank for the precooling treatment.

For the precooling condition, subjects were seated in cool water (approximately $25^{\circ}\text{C}/77^{\circ}\text{F}$) up to their hips for 40 minutes, until the onset of continuous shivering, or until T_c decreased by 1.0°C . All subjects completed the entire 40 minutes of precooling without the development of continuous shivering or T_c reductions of 1.0°C . Core temperature was recorded every fifth minute during precooling and every minute during the following RE measurement. In most cases, the temperature sensor was passed within 24 hours although in one subject, the device was passed after six days. During the precooling condition, heart rate was recorded by the heart rate monitor every 15 seconds and blood pressure was measured every 10 minutes. Immediately following the precooling trial, flexibility was reassessed by the sit and reach test and the subject completed the RE trial as performed in the two previous testing sessions. Early into the investigation, T_c recordings during the RE trial became erratic and

determination of T_c became difficult while the subject was running. However, T_c recordings were stable when the subject was standing. Thus, at five minute intervals during the RE trial each subject was prompted to move to the side of the treadmill for T_c recording. Each break lasted between five and ten seconds.

The investigator met with each subject within 48 hours following sensor ingestion to confirm that the sensor had been passed. Subjects did not ingest a second sensor until confirmation that the first sensor had in fact been passed.

Control Trial

For the control trial, the subject ingested a second temperature sensor as previously described and reported back to the laboratory. Proper sensor functioning was determined, the heart rate monitor was fitted, and body weight was recorded prior to the sit and reach test. Instead of the precooling treatment, study participants rested in room air for forty minutes in a seated position similar to the precooling trial. Heart rate, T_c , and blood pressure were measured at the same intervals as during the precooling trial. Flexibility was reassessed following the control condition just prior to RE measurement. Brief pauses on the side of the treadmill were completed every five minutes during the running portion of the RE trial for T_c recording.

Subjects were asked to refrain from training on testing days and to refrain from intense running, cycling, and weight training workouts which may cause muscular damage and alterations in RE during the testing period. Additionally, RE is influenced by extreme air temperature. Thus, experimental trials occurred at a mean lab temperature of 23.4 ± 1.32 °C (range 18.5 - 26°C).

Statistical Analysis

Investigators calculated mean values of relative and absolute oxygen consumption (VO_2), heart rate, minute ventilation (V_E), T_c , and sit and reach scores utilizing Microsoft Excel. Differences between the experimental and control trials were determined by univariate analysis of variance (ANOVA) of the mean data with the SPSS 15.0 software package (SPSS, Inc, Chicago, IL).

This procedure was used as an alternative to ANOVA with repeated measures as this method eliminates entire subjects if a single data point is missing. Due to the difficulty in attaining accurate T_c data, all but one subject had a least one missing data point. Sex differences were determined by analyzing data from the male and female subjects during a single condition, such as the control day. Differences in test variables within a sex were determined by only selecting data from one sex at a time and then performing the analysis. Additional descriptive variables such mean VO_{2max} , bodyweight, percentage of body fat, height, and age were determined using the Excel program. Significant differences between women and men were determined using the SPSS software. Any p-value less than .05 was considered statistically significant.

Chapter IV Results

Fourteen of the 18 subjects that were recruited completed all four testing sessions, eight of these subjects were male, six of these subjects were female. One female subject completed the control trial only. Ambient temperatures ($23.4 \pm 1.3^{\circ}\text{C}$) and humidity ($40.6 \pm 15.0\%$) were neutral throughout the course of the study. Table 4.1 displays the mean age, height, weight, and percent body fat of the subjects.

Table 4.1: Mean and standard deviation of age, height, bodyweight, and percent body fat of subjects.

	All subjects (n=15)	Male subjects (n=8)	Female subjects (n=7)
Age (yrs)	26.6 (5.0)	26.3 (6.0)	27.0 (4.0)
Height (m)	1.74 (0.1)	1.78 (0.1)	1.69 (0.0)*
Bodyweight (kg)	65.7 (8.5)	71.8 (4.9)	58.7 (5.9)*
% Fat	13.3 (6.0)	10.0 (5.5)	17.2 (4.2)*

* $p \leq 0.05$ compared to male subjects

Subject characteristics

Mean (\pm standard deviation) $\text{VO}_{2\text{max}}$, ten kilometer run times, and percent $\text{VO}_{2\text{max}}$ of the running economy (RE) trial of the subjects are displayed in Table 4.2. These results indicate that the subjects were in fact highly-trained runners. While the RE trial was designed to represent similar workloads between sexes, the female subjects ran at a significantly higher percentage of their $\text{VO}_{2\text{max}}$ compared to the male subjects.

Table 4.2: Mean and standard deviation maximal oxygen consumption and 10 kilometer run time.

	All subjects (n=15)	Male subjects (n=8)	Female subjects (n=7)
$\text{VO}_{2\text{max}}$ (ml/kg/min)	58.6 (7.2)	64.3 (3.3)	52.0 (3.5)*
10km time (min)	38.1 (4.6)	34.9 (2.7)	42.6 (2.4)*
% $\text{VO}_{2\text{max}}$ of RE trial	71 (6)	67 (4)	75 (4)*

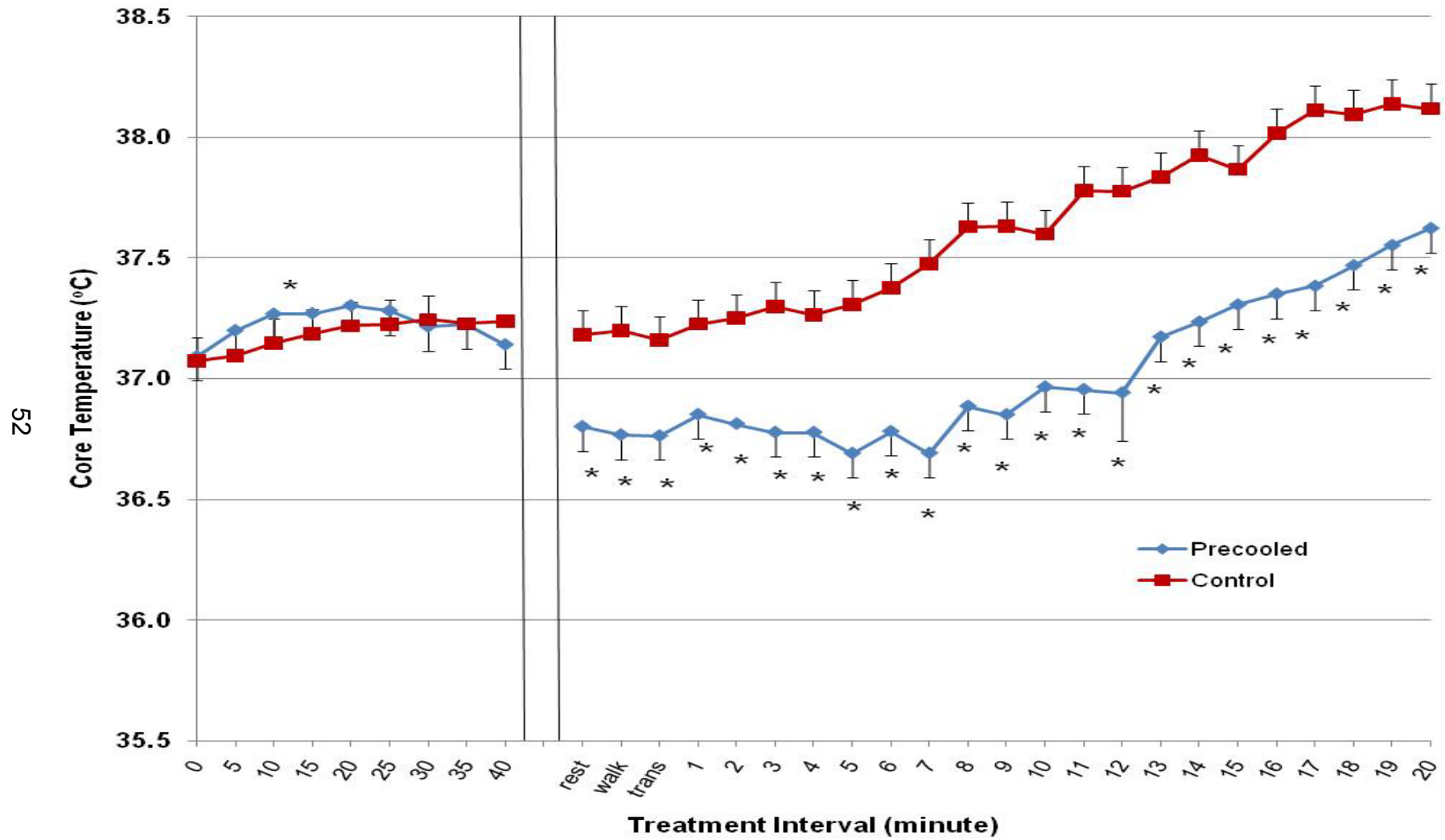
* $p \leq .05$ compared to male subjects

Exercise variables

Core temperature

The purpose of the precooling procedure was to reduce core temperature (T_c) relative to the control condition. Figure 4.1 displays mean T_c at five-minute intervals during the water immersion and control condition and for one-minute intervals during the RE trials from both the precooled and control days. Core temperature during the water immersion tends to be slightly higher from minute 5 to minute 25 (mean difference = 0.1°C) when compared to the control condition, although this difference is significant only at minute 10. However, by the start of RE measurement, T_c is significantly lowered (mean reduction = 0.4°C) following precooling. The lowest mean T_c ($36.7 \pm 0.3^\circ\text{C}$) occurred eight minutes into the RE trial (min 5 of running) and the greatest average difference between trials (0.76°C) occurred 12 minutes into the RE trial (min 9 of running).

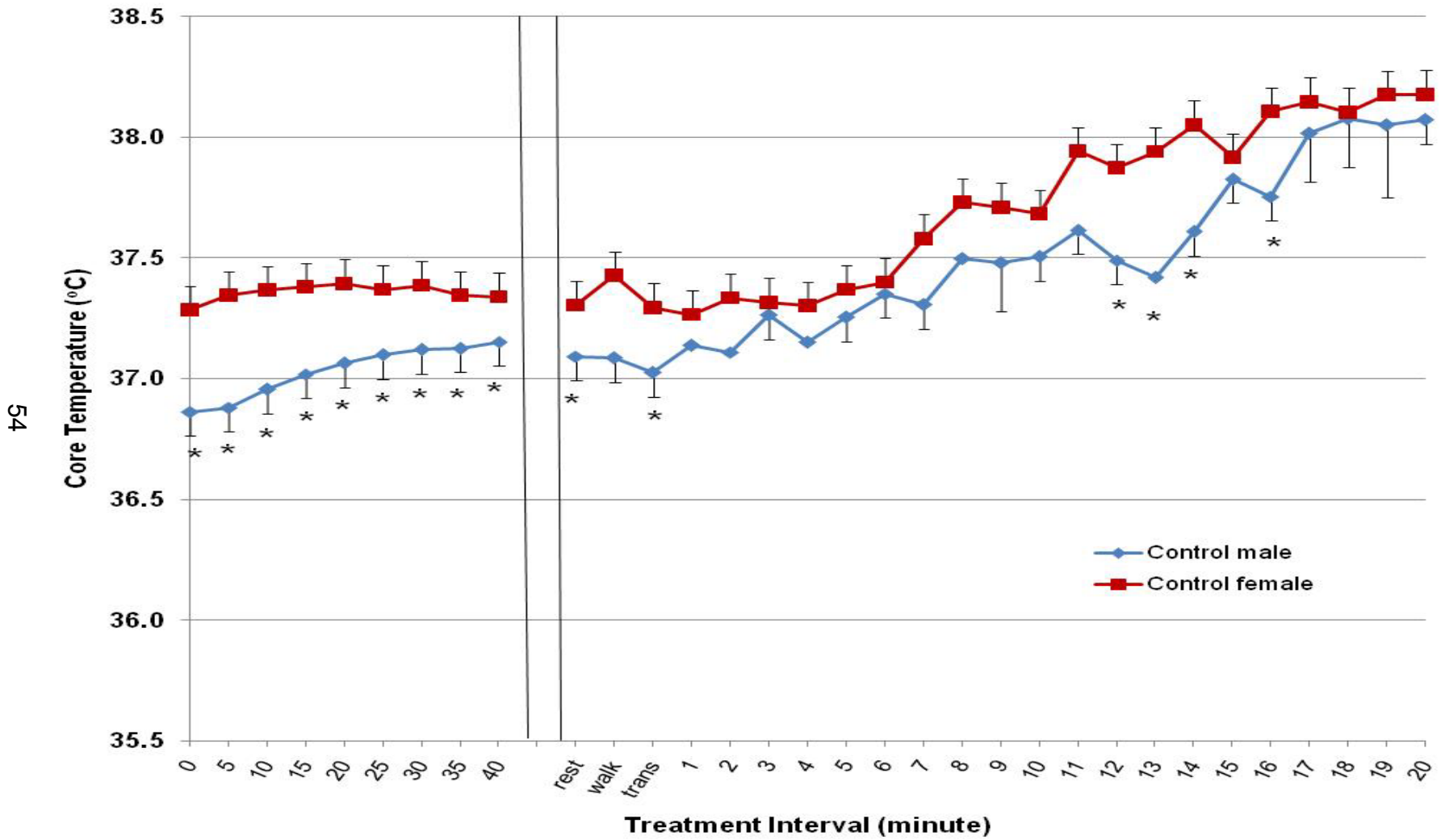
Figure 4.1: Mean core temperature of all subjects.



* significantly different from control condition $p < .05$

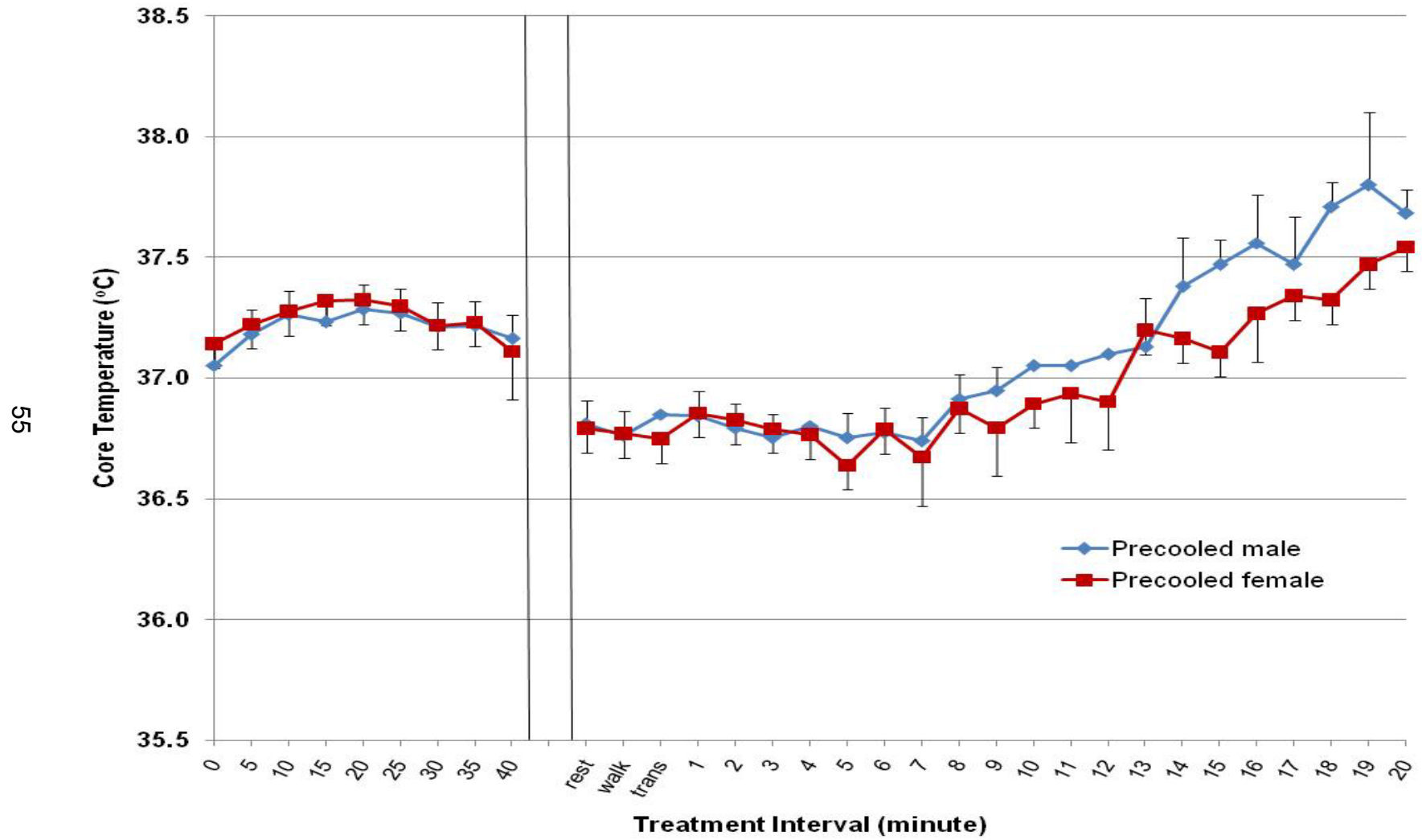
Figure 4.2 displays mean T_c values of the subjects during the control condition and Figure 4.3 displays mean T_c values of the subjects during the precooled condition. There was a main effect of sex with the male subjects displaying a significantly lower T_c when compared to the female subjects during the control trial beginning at the baseline (min 0) of the session (mean decrease = 0.2°C , $p = .010$). This decrease in T_c persisted throughout the RE trial with T_c averaging 0.2°C lower in the male subjects. However, this effect was not present during the precooling trial. In fact, during the precooling trial the male subjects demonstrated a small elevation in T_c (average increase over the whole trial = 0.1°C) when compared to the female subjects, although this difference was not significant.

Figure 4.2: Mean core temperature values of the subjects during the control condition.



* significantly different from female subjects p < .05

Figure 4.3: Mean core temperature values of the subjects during the precooled condition.



Oxygen consumption

Mean relative oxygen consumption for both the entire control and precooling trials are displayed in Figure 4.4. The averaging interval included values from the 20-minute running bout, and excluded values from the rest, walk, and acceleration minute. There were no significant differences in mean oxygen consumption following precooling for either male or female subjects. Figure 4.5 shows the mean relative oxygen consumption for each minute during the RE trials. Precooling did not result in any significant differences in oxygen consumption when compared to the control trial.

It is important to note that with the exception of T_c , responses of the male and female subjects cannot be directly compared to one another due to the difference in treadmill workload. While the male subjects ran at a velocity of 8.6 mph, the female subjects ran at a velocity of 8.0 mph making direct comparisons of heart rate, VO_2 , and V_e between sexes irrelevant. However, changes in these variables among sexes were compared.

Figure 4.4: Overall mean relative oxygen consumption (\pm standard error) for precooled and control trials.

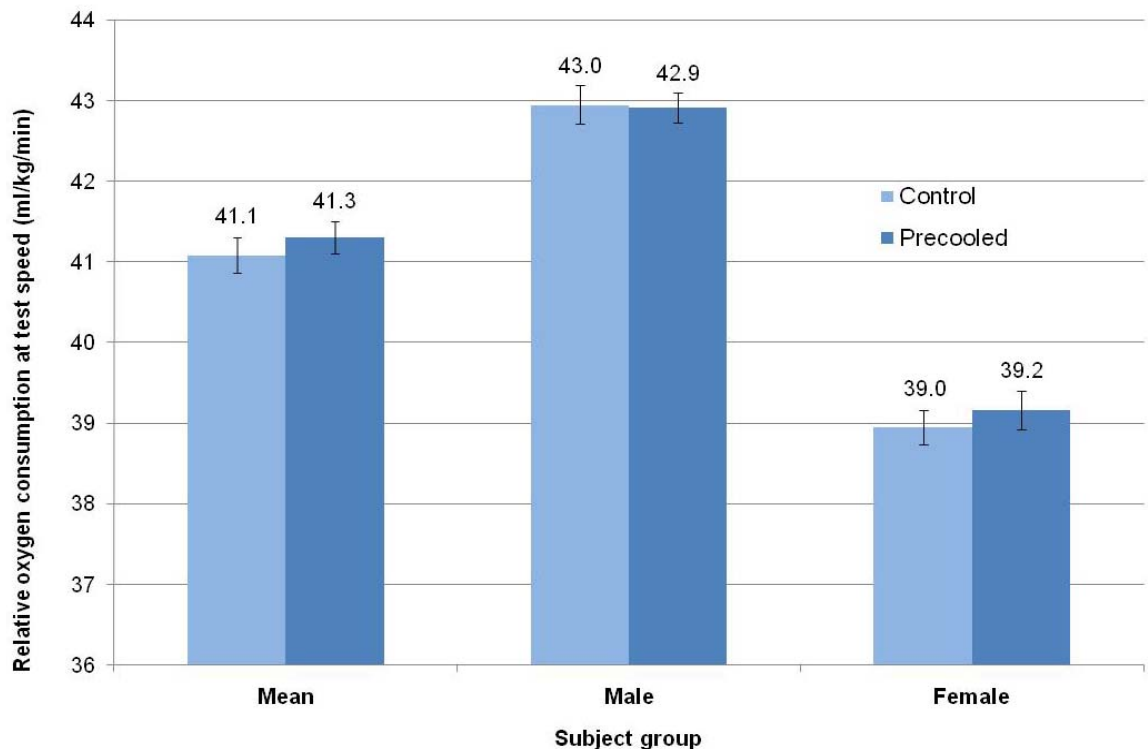
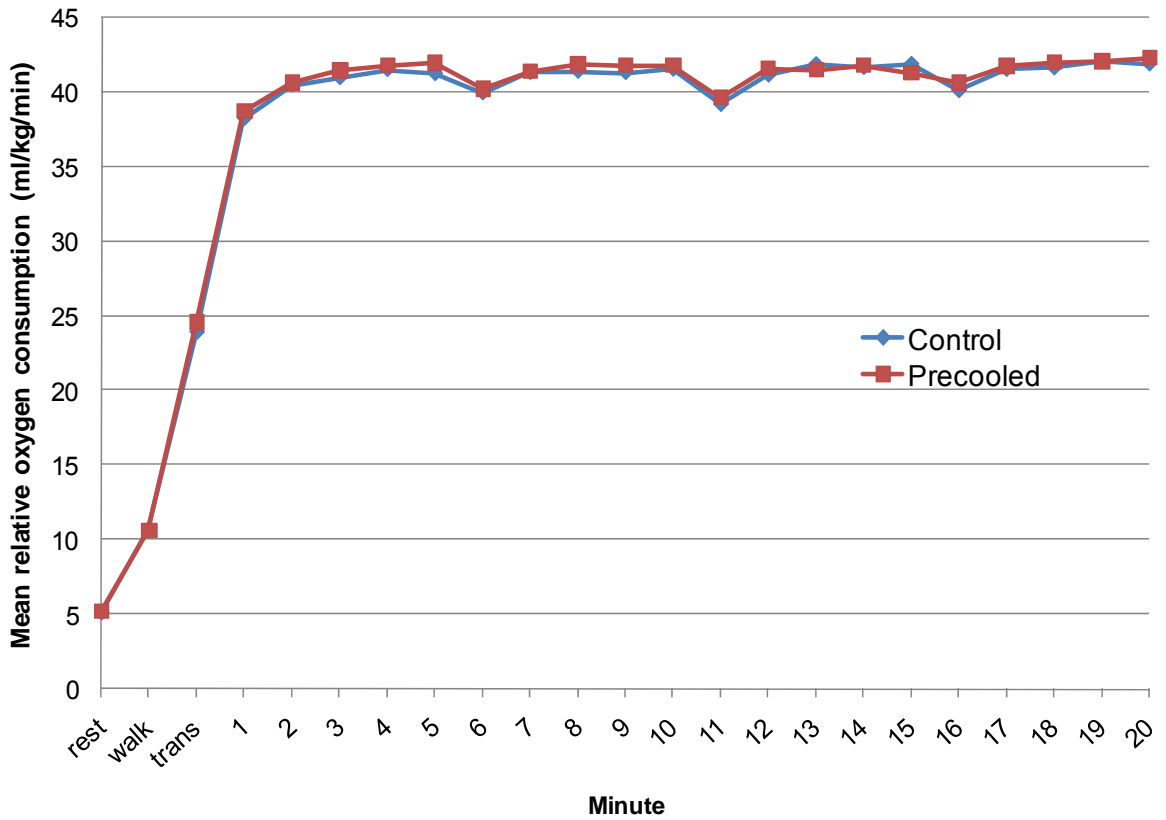


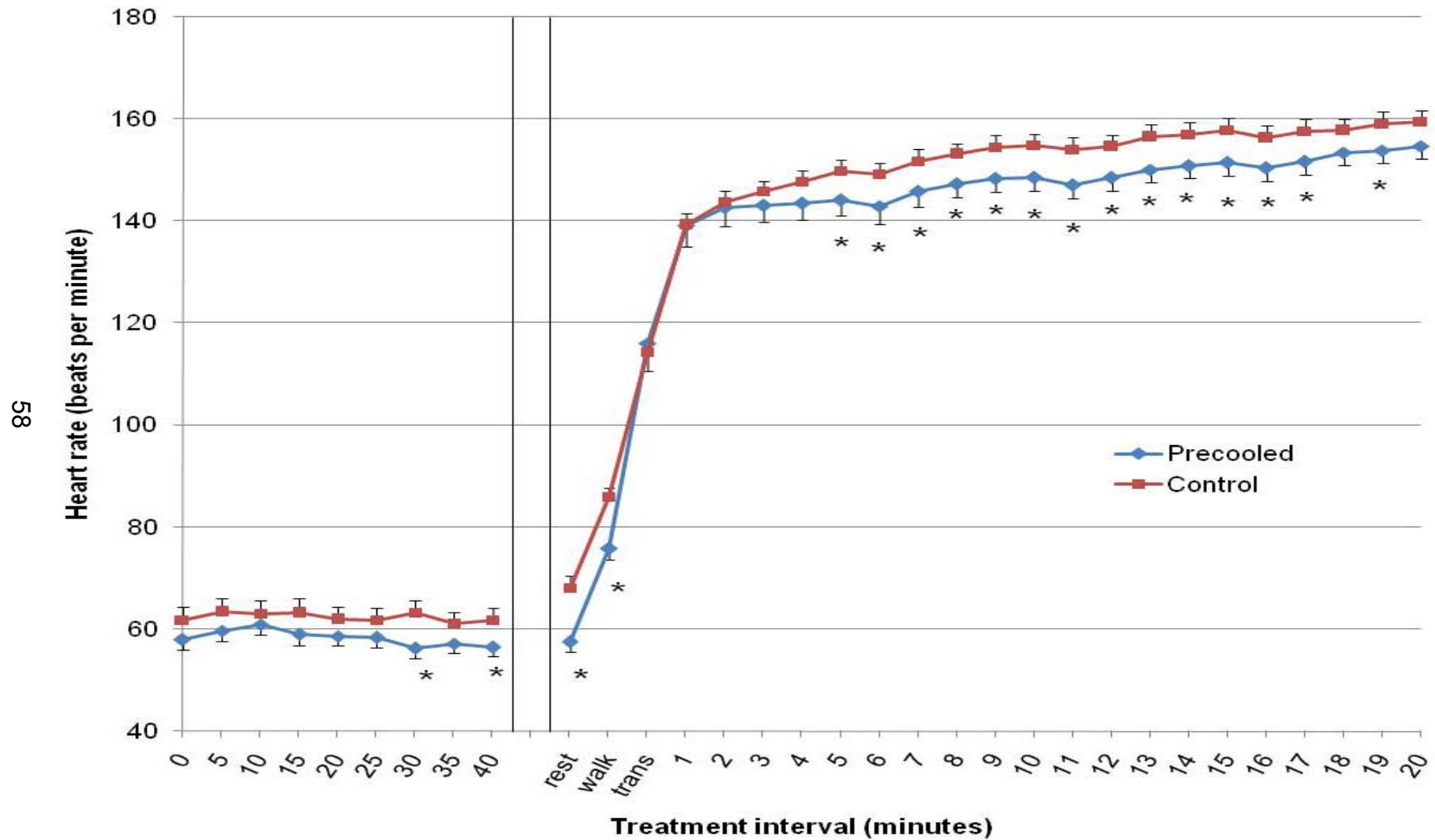
Figure 4.5: Minute-by-minute mean relative oxygen consumption during precooled and control conditions for all subjects.



Heart rate

Mean heart rate values are displayed in Figure 4.6 for all subjects. Heart rate was significantly reduced during the water immersion and the running trial following precooling when compared to the control condition on average by five beats per minute (bpm). The asterisks denote specific points of statistically significant reductions in heart rate.

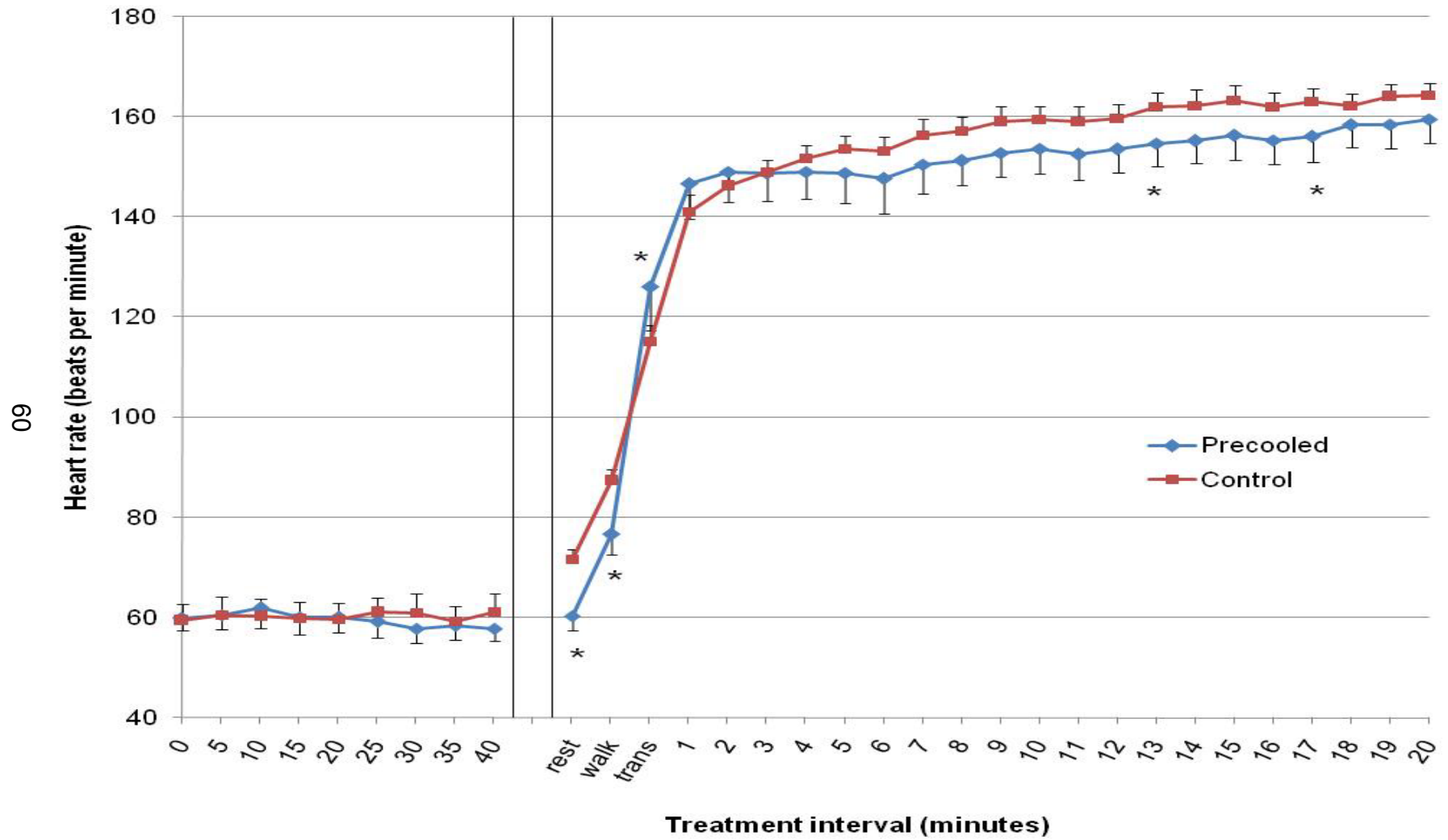
Figure 4.6: Mean heart rate during precooled and control conditions for all subjects



* significantly different from control condition $p < .05$

Mean heart rate values for the female subjects are displayed in Figure 4.7. The female subjects demonstrated similar heart rates during both treatments, whereas the male subjects displayed significantly lower heart rates during the precooling treatment (mean reduction = 6 bpm) compared to the control (see Figure 4.8). During the RE trial, heart rate was reduced in the female subjects for the rest and walk minute and actually increased above control values during the transition minute. Heart rate was significantly lower when compared to the control trial at two other time points (min 13 and 17 of running).

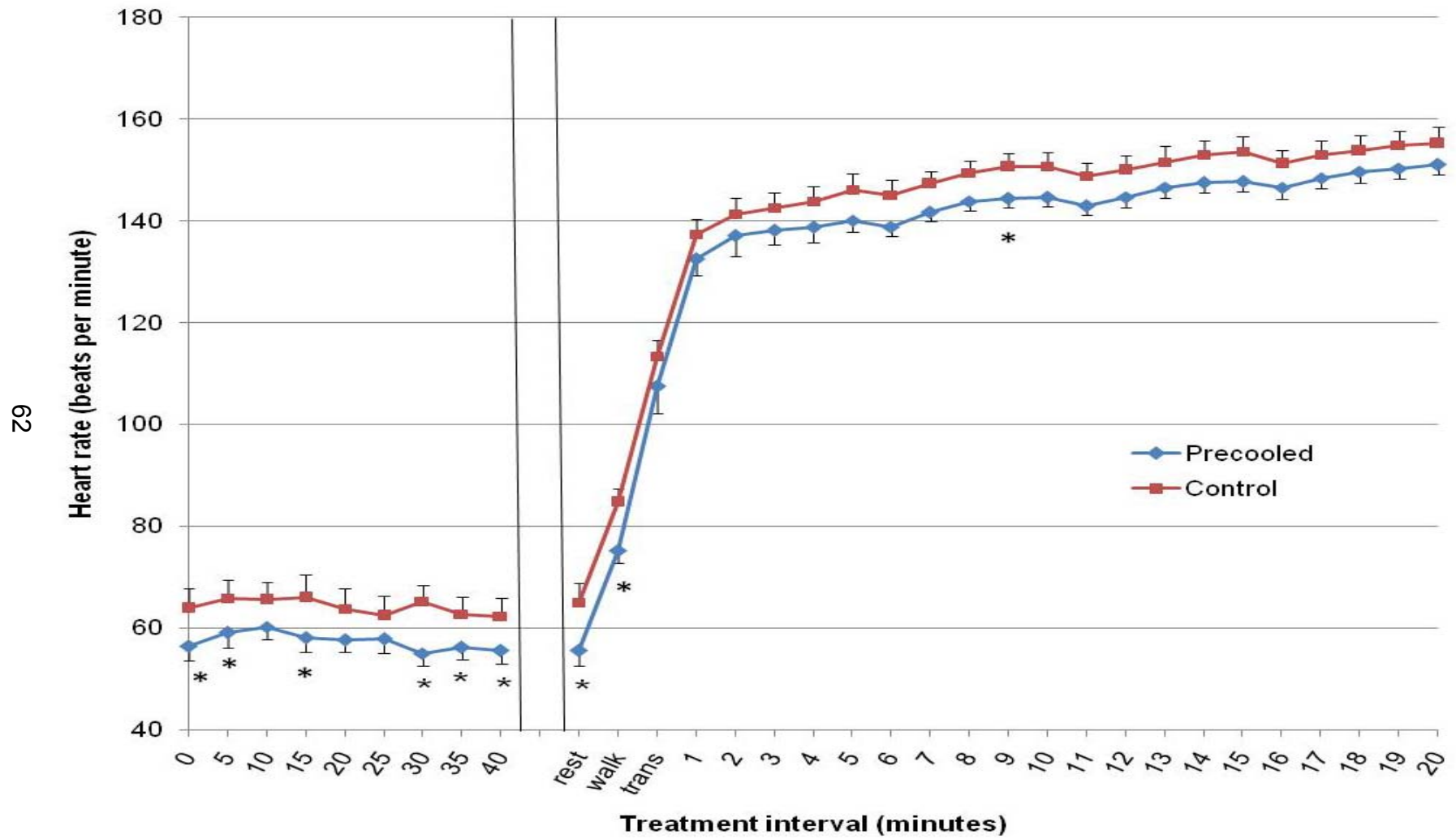
Figure 4.7: Mean heart rate during precooling and control condition for female subjects.



* significantly different from control condition p<0.05

For the male subjects, the average reduction in heart rate was six beats per minute over the entire precooling trial. Heart rate was significantly reduced during most of the precooling trial and during the rest and walk minutes of the RE trial. Heart rate was significantly lower at one additional time point (minute 9 of running) during the precooled condition.

Figure 4.8: Mean heart rate during precooling and control condition for male subjects.



* significantly different from control condition $p < .05$

Minute ventilation

Mean minute ventilation values are presented in Figure 4.9 for all subjects. There were no significant differences between conditions for any time point during the RE trials. Minute ventilation for the male subjects is presented in Figure 4.10. Again, there were no significant differences between trials. However, for the female subjects V_E was significantly lower in the precooling trial by an average of 1.4 liters per minute ($p = .000$). These data are presented in Figure 4.11.

Figure 4.9: Minute ventilation during precooled and control trial for all subjects.

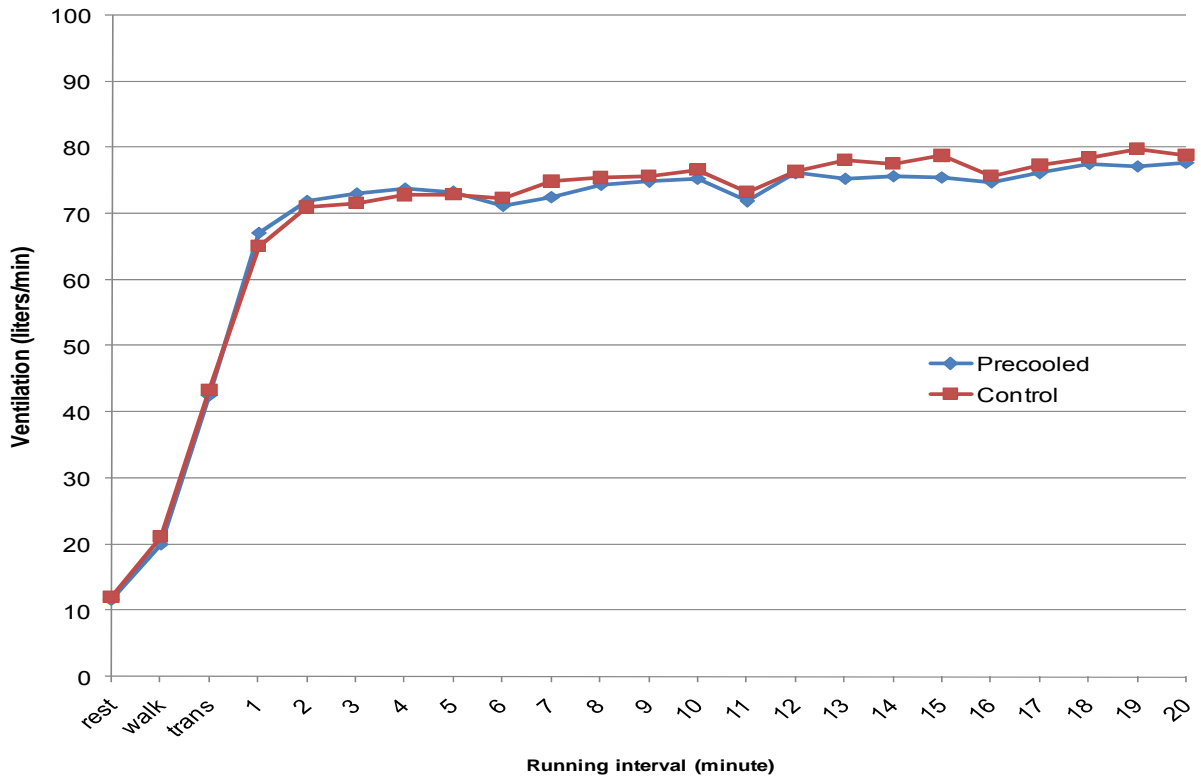


Figure 4.10: Minute ventilation during precooled and control conditions for male subjects.

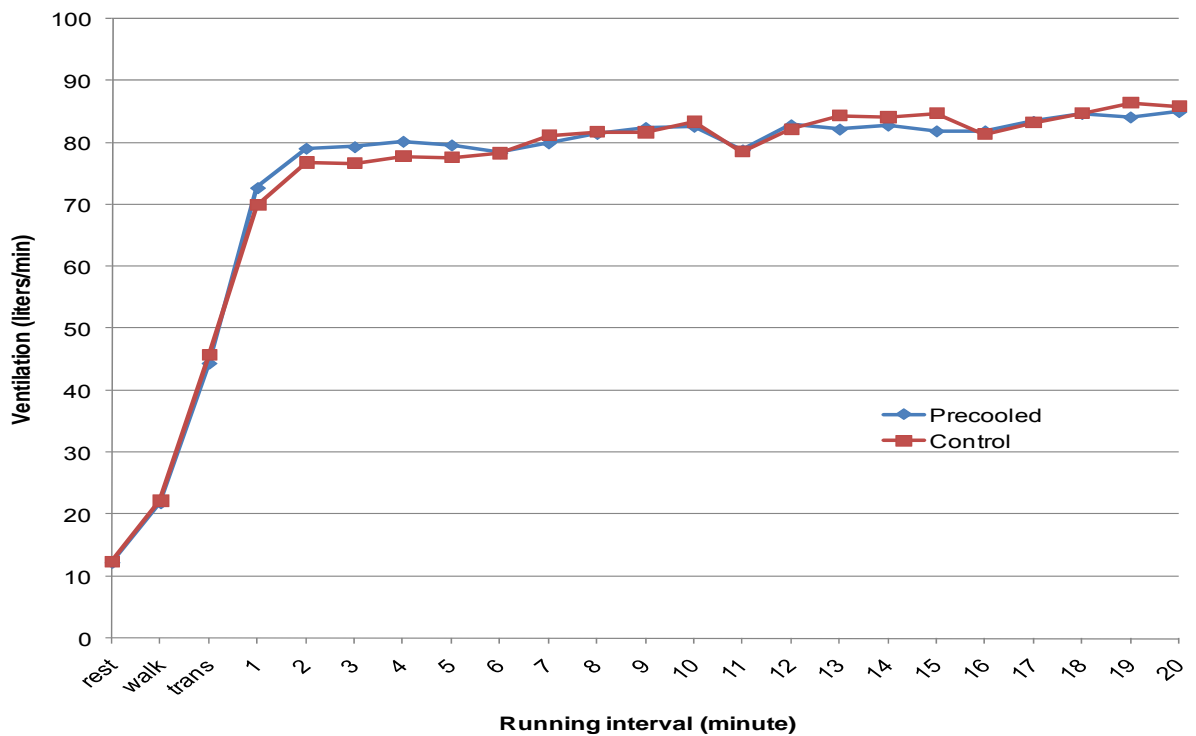
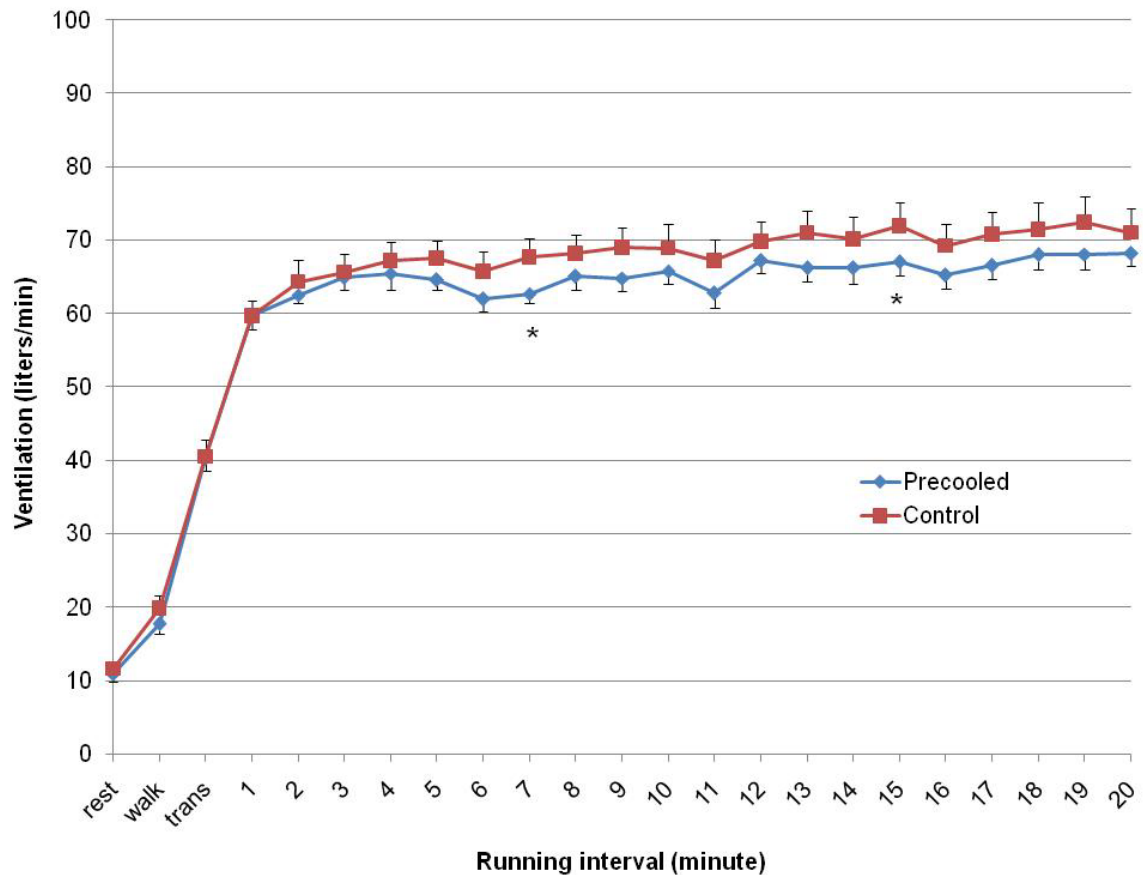


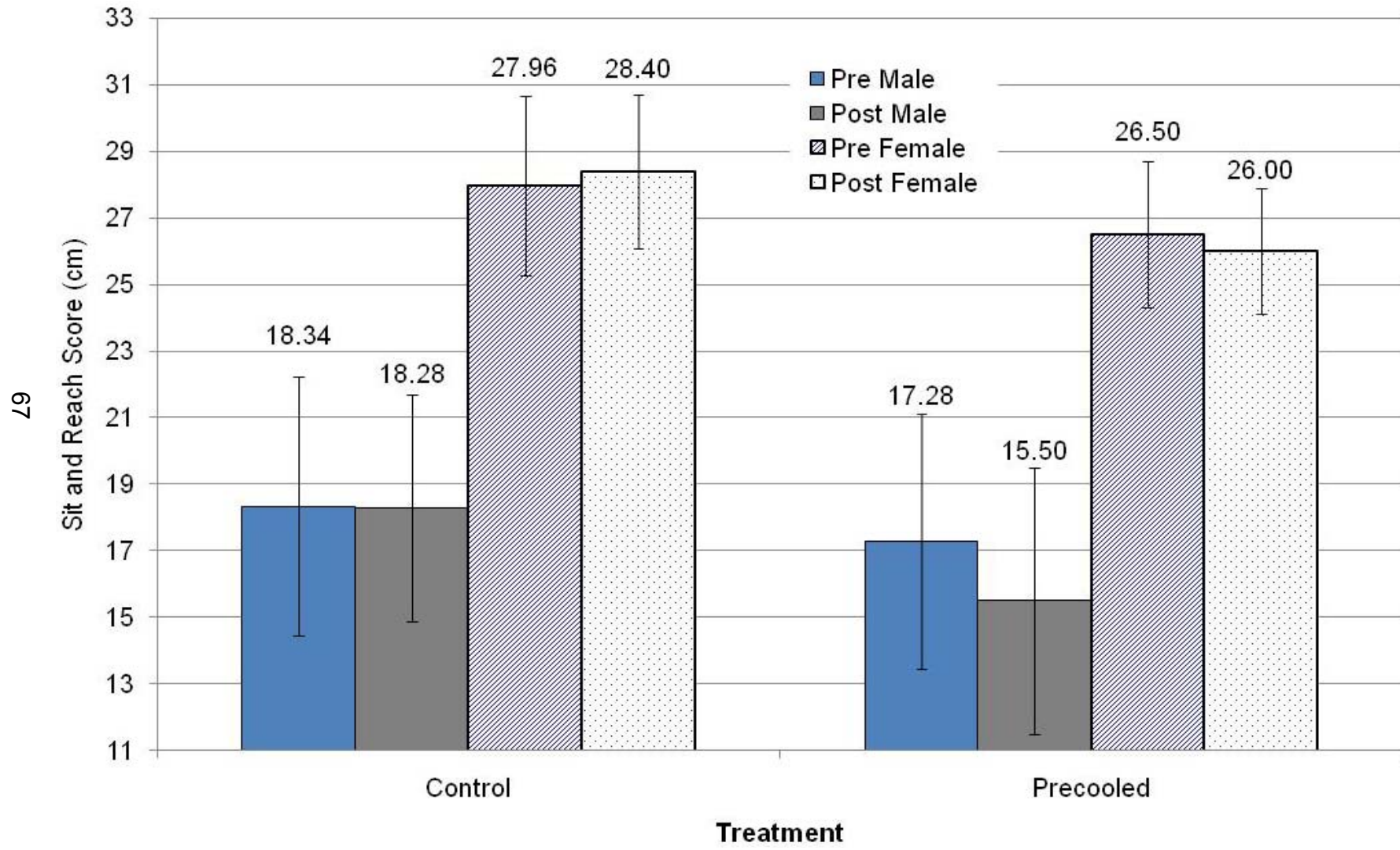
Figure 4.11: Minute ventilation during precooled and control conditions for female subjects.



Flexibility

Sit-and-reach score was measured both prior to and following the precooling and control treatments. There was a main effect of sex, indicating that the female subjects were more flexible at all time points compared to the male subjects ($p = .039$). Following the control condition, sit and reach score decreased in the male subjects and slightly increased in the female subjects, although these differences were not significant. However, following water immersion, sit and reach score decreased slightly in the female subjects (mean \pm SE change in sit-and-reach score = 0.5 ± 0.7 cm, $p > .05$) while the male subjects demonstrated a much larger decrease in flexibility (mean \pm SE decrease = 2.78 ± 0.5 cm). The main effect of treatment was significant in the male subjects ($p = .016$) indicating that sit and reach score was lower in the precooled condition. However, this effect was partially due to a reduced mean score in the pre-test on the precooling day, thus the difference pre to post-cooling was non-significant.

Figure 4.12: Mean sit and reach scores (\pm standard error) before and after precooling and control conditions.



Correlations

Previous literature has suggested that a number of significant correlations exist between RE and flexibility and RE and performance (13, 16, 23, 31, 38). On the other hand, among a group of athletes homogenous for VO_{2max} , performance time should not be significantly associated with VO_{2max} (13, 38, 55). For the current study, correlations between VO_{2max} and 10km performance time are presented in Figure 4.13. For the female subjects, the association between VO_{2max} and 10km performance is significant ($r^2 = 0.793$, $p = .007$) indicating that those athletes with the highest VO_{2max} outperform those with lower VO_{2max} values. This is not true of the male subjects in which no significant relationship is evident, confirming that the male subjects are homogenous for VO_{2max} . With the exception of one subject ($VO_{2max} = 56.5$ ml/kg/min), the VO_{2max} values of the male athletes are within the range of 64 to 67.2 ml/kg/min.

Figure 4.13: Correlation between VO_{2max} and 10km time for male and female subjects.

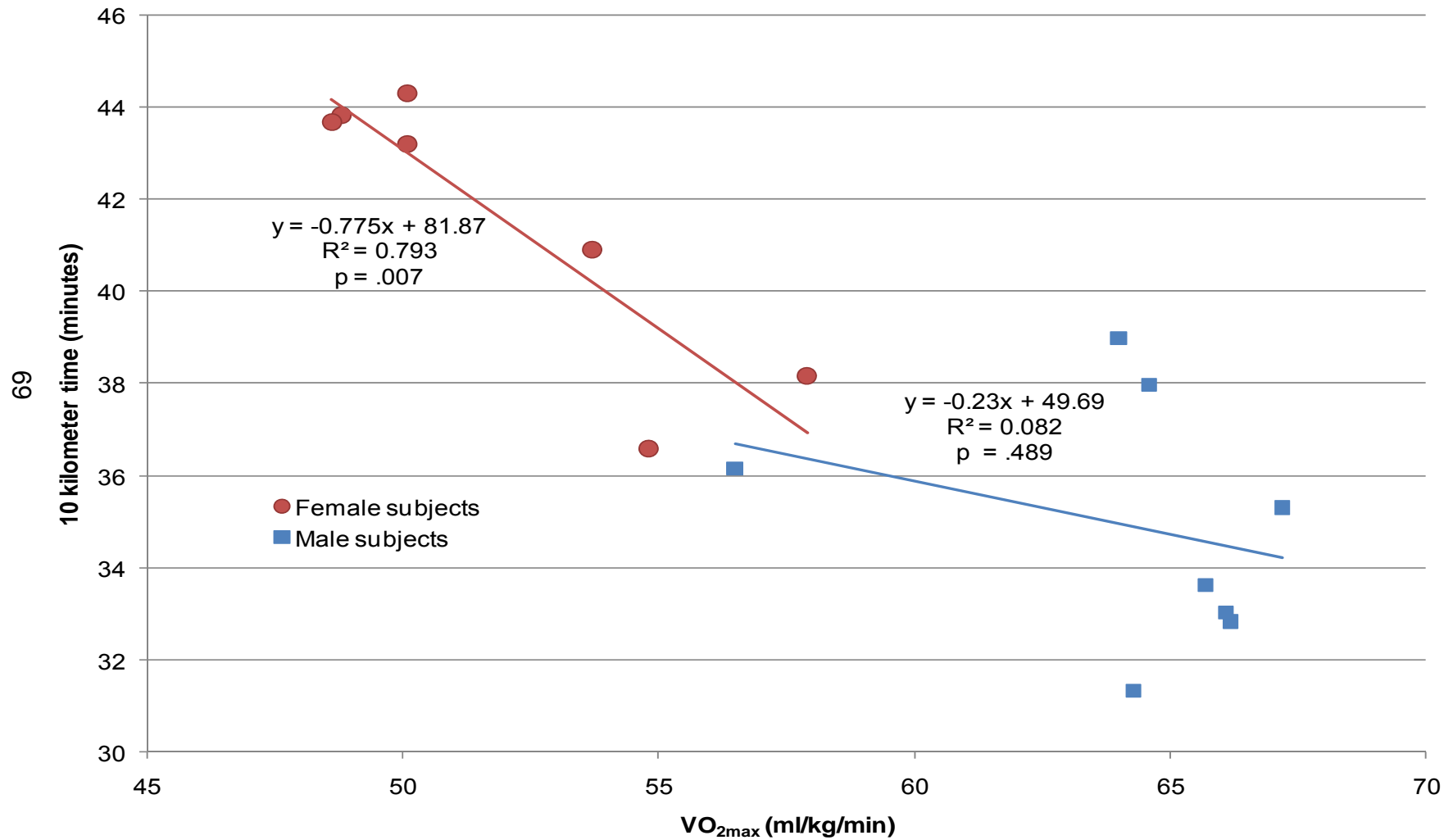
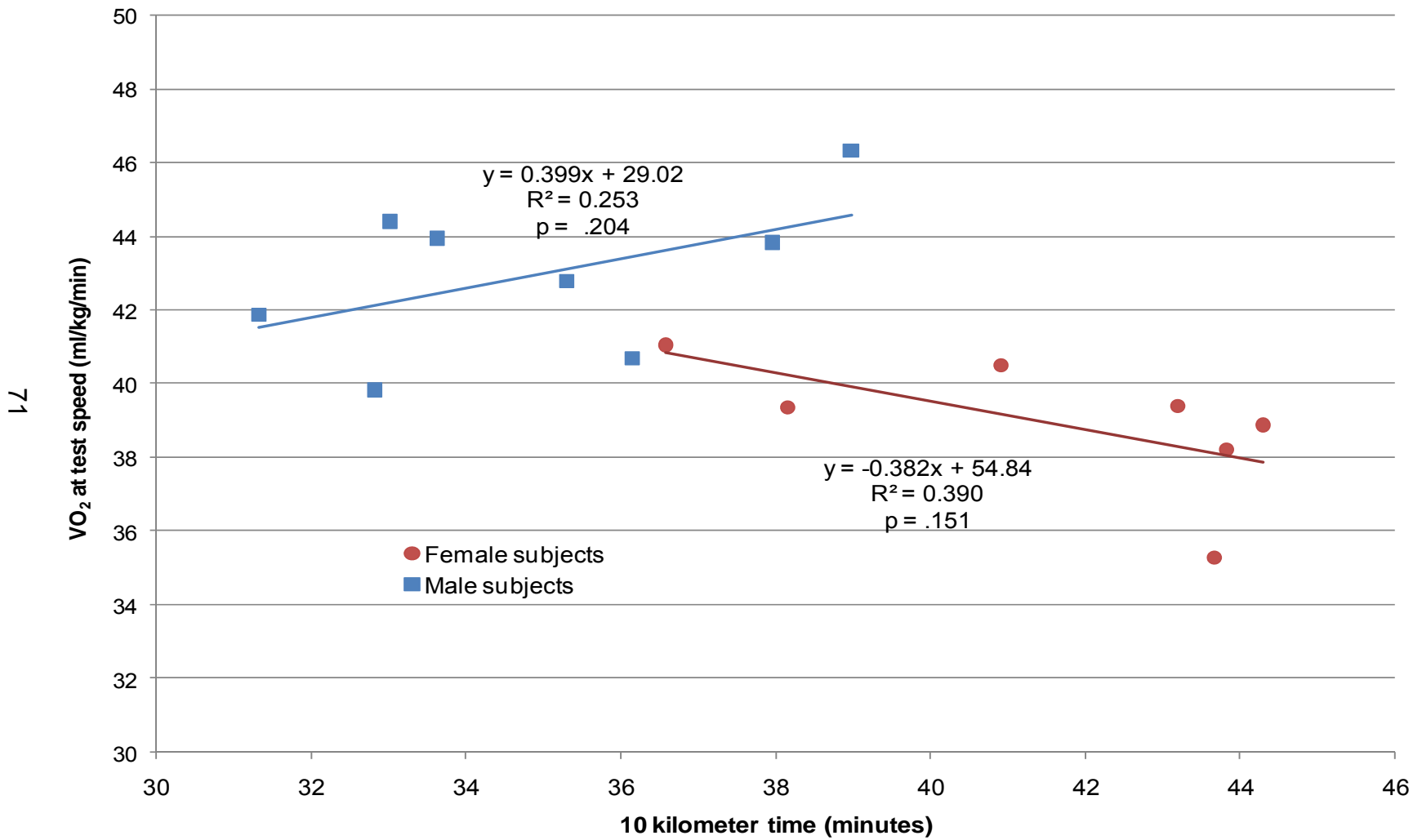


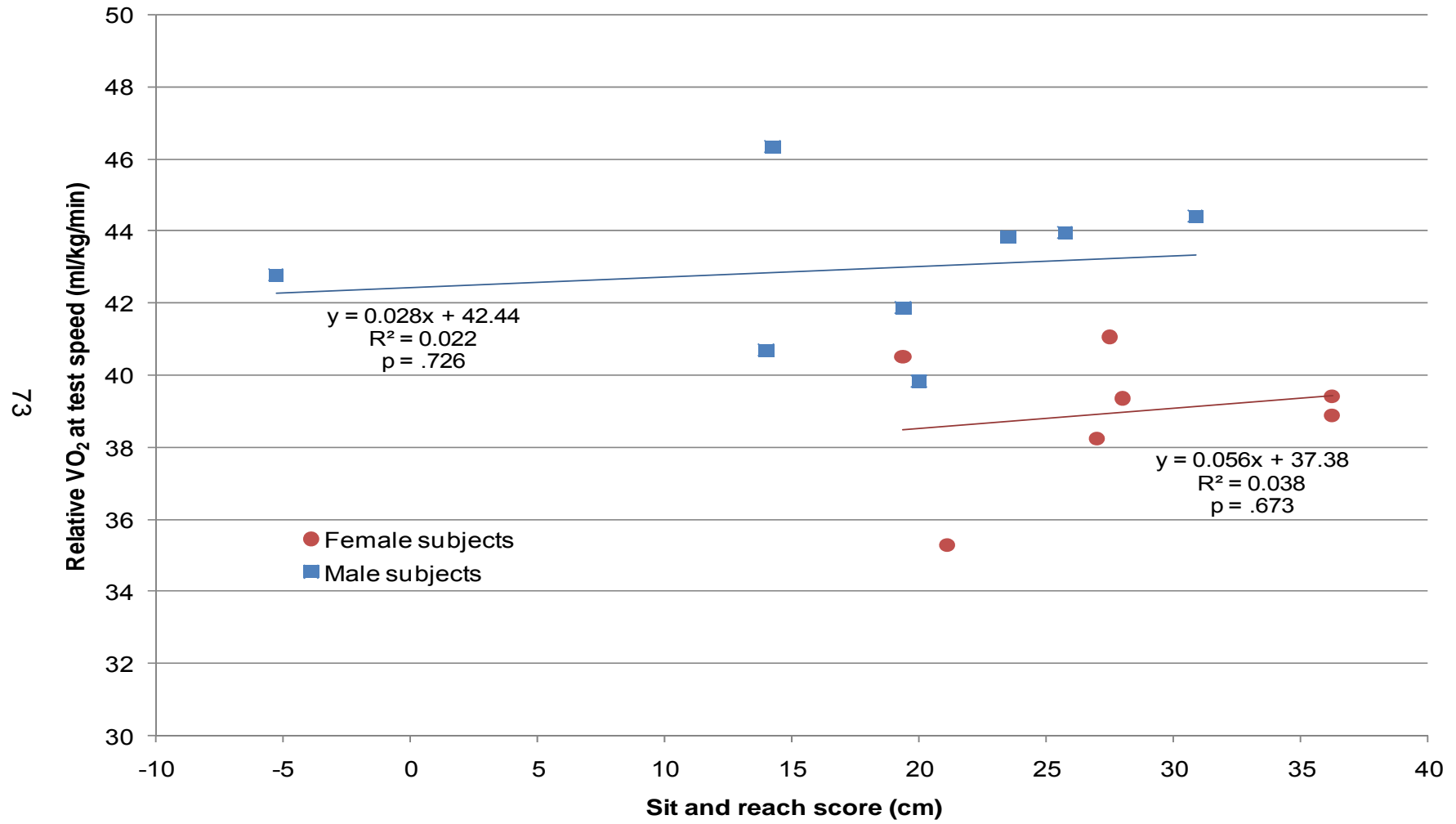
Figure 4.14 demonstrates the relationship between RE and 10km performance for all subjects. In a group of athletes homogenous for VO_{2max} , differences in RE can explain up to 65% of the variation in running performance (13, 38). The relationship between RE and 10km performance should be positive to reflect that those athletes who consume more oxygen at a given workload also demonstrate greater times to complete the 10km distance. For the male subjects, the relationship between RE and 10km time is positive, however it is not statistically significant ($p = .204$). For the female subjects the relationship is in the opposite direction suggesting that the fastest runners also demonstrate the worst economy, however the relationship between these two variables is insignificant.

Figure 4.14: Correlation between 10km time and running economy.



Multiple authors have demonstrated significant correlations between flexibility and running economy (16, 23, 31) among a variety of subjects and across a number of treadmill velocities. Again the relationship is positive indicating that the most flexible individuals consume more oxygen at a given workload. Correlations between sit and reach score, a measure of lower-body flexibility, and oxygen consumption for the current study are presented in Figure 4.15. While the relationship is positive for both groups of subjects, neither correlation is statistically significant.

Figure 4.15: Correlation between sit and reach score and running economy.



Chapter V

Discussion

The purpose of this study was to determine if a precooling procedure reduced oxygen consumption during treadmill running, commonly referred to as running economy. In addition, sex differences in response to precooling were also examined. The main findings of this study indicate that the precooling procedure was effective in reducing core temperature (T_c) and heart rate in all subjects, and minute ventilation (V_E) in the female subjects, however oxygen consumption (VO_2) did not change from the control condition. Female subjects demonstrated a different heart rate and V_E response when compared to the male subjects, indicating that there is a difference between sexes in response to this treatment. Correlation analysis between running economy (RE), running performance, VO_{2max} , and sit and reach revealed only one significant correlation, between VO_{2max} and performance, in the female subjects. Analysis of the results will be divided into four sections; subject characteristics, response of all subjects combined, differential responses between sexes, and correlation analyses.

Subject characteristics

It was the intent of this study to recruit high-level runners between the ages of 18 and 45 for participation in the research procedures. The mean age of all subjects was 26.6 years, with the average age of the female subjects slightly older than the male subjects. The female athletes were significantly shorter, weighed less, and had a greater percentage of body fat than their male counterparts.

Mean VO_{2max} values (64.3 ± 3.3 ml/kg/min) and 10 km performance times (34.9 ± 2.7 minutes) of the male runners confirm that they were in fact well-trained athletes. These subjects on average had lower VO_{2max} values and slower 10 km times than the athletes in some studies (8, 13, 19, 31, 40), but were equally or more trained than the athletes in several studies (16, 38, 41, 42, 55,

57) reviewed in Chapter 2 including the study by Folland et al. (22) in which RE was the variable of interest following cooling. The mean VO_{2max} values (52.0 ± 3.0 ml/kg/min) and 10 km performance times (42.6 ± 2.4 ml/kg/min) indicate the female athletes were less trained than the athletes included in the studies by Daniels (19) and Morgan (40) and more trained than the female athletes in three other studies (8, 42, 56). Thus, the current group of subjects describe runners with an average cardiovascular fitness level and 10km performance times when compared to previous running economy literature.

The RE trial represented on average $67 \pm 4\%$ of VO_{2max} for the male athletes and $75 \pm 4\%$ of VO_{2max} for the female athletes. Since the treadmill workloads were fixed for each sex (8.6 mph for males, 8.0 mph for females) and RE is known to vary widely at any given velocity (16, 31), the variation in this measure was not surprising.

Response to precooling of all subjects

Core temperature

The primary purpose of any precooling procedure is to reduce T_c of the subjects. Water temperature during the precooling trial averaged $24.8 \pm 0.1^\circ\text{C}$. All subjects were able to complete the entire precooling trial without the onset of continuous shivering or a decline in T_c exceeding 1.0°C . The mean T_c at minute 0 of the precooling procedure was 37.09°C . By the end of the 40-minute water immersion, mean T_c was slightly elevated to 37.14°C . However, by the beginning of the RE trial which began seven to 15 minutes following water immersion, mean T_c dropped to 36.80°C . The lowest mean T_c of the precooling trial (36.73°C) occurred at minute 8 of the RE trial, or during the fifth minute of running. Mean T_c reached baseline values by minute 13 of running and the maximum mean T_c of 37.65°C occurred at the end of the RE trial.

Baseline T_c for the control trial was 37.07°C and was slightly elevated to 37.24°C at the end of the control treatment, which consisted of quiet sitting in room air (mean air temperature = $22.8 \pm 1.4^\circ\text{C}$) for 40 minutes. At the start of the RE trial mean T_c was 37.18°C , an increase of 0.4°C above the precooled

condition. The lowest mean T_c of the control trial (37.16°C) occurred at minute 3 of the RE trial, as the athletes accelerated to the sex-specific treadmill velocity. Mean T_c remained elevated above baseline values for the entire duration of the control treatment and RE trial. The maximum mean T_c of 38.12°C occurred at minute 20 of treadmill running.

Thus, the precooling procedure did in fact reduce T_c significantly ($p = .000$) when compared to the control condition. Core temperature increased slightly during both the precooling and control treatments, however T_c was dramatically reduced by the beginning of the RE trial in the precooling condition and continued to drop until the fifth minute of running. Baseline values were not reached until 13 minutes of running in the precooled condition, whereas T_c exceeded baseline values at every time point in the control condition. The change in T_c from minimum to maximum due to the exercise protocol was similar during both treatments and averaged 0.99°C .

While T_c measurements during both the precooled and control treatments were stable, T_c measurements during running, and in some cases walking, became erratic and unusable for data analysis. For some time points, as few as five values out of a possible 15 were available to generate mean values. Due to lack of stability in T_c measurements, brief stops of only five to 10 seconds at five-minute intervals during the treadmill run were incorporated to ensure an accurate T_c recording. Thus, mean values from minute 5, 10, 15, and 20 of running were generated from more values and thus represent the T_c response most accurately. These brief stops had a small effect on VO_2 and heart rate data which will be discussed in the next sections.

In comparison to previous literature, the reduction in T_c was similar to those protocols utilizing cool water immersion of similar duration (see Tables 2.1 – 2.4). In the current study, T_c was reduced 0.3°C for all subjects following precooling at the onset of exercise. However, T_c continued to drop during the RE trial in the precooling condition ultimately reducing T_c by 0.4°C when compared to the control condition. This “afterdrop” in T_c is a common finding in the literature (3, 4, 6, 7, 10, 12, 18, 21, 22, 30, 33, 36, 37, 43, 47, 58) and is typically attributed

to both conductive and convective heat loss from the core to colder layers of tissue on the periphery (35).

Oxygen consumption

The variable of interest in the current study was RE which is the volume of oxygen consumed to run at a specific velocity and is expressed relative to bodyweight. Mean VO_2 value for the male subjects running at 8.6 mph (or 7 minutes/mile) was 43.0 ± 2.12 with a range from 39.8 to 46.3 ml/kg/min. The mean VO_2 value for the female subjects running at 8.0 mph (or 7.5 minutes/mile) was 39.0 ± 1.88 with a range from 35.3 to 41.0 ml/kg/min. These values are comparable to other studies in which similar treadmill velocities were tested (see Table 5.1).

Table 5.1: Mean VO_2 (\pm standard deviation) values from current and previous studies.

Study	Male subjects		Female subjects	
	Speed (mph)	Mean VO_2 (ml/kg/min)	Speed (mph)	Mean VO_2 (ml/kg/min)
Current Study	8.6	43.0 ± 2.1	8.0	39.0 ± 1.9
Conley and Krahenbuhl ¹³	9.0	44.7	-	-
Craib et al. ¹⁶	9.25	$45.4 \pm 0.6^*$	-	-
Davies et al. ²⁰	-	-	8.0	44.7 ± 2.4
Morgan et al. ⁴⁰	8.0	38.9	8.0	39.3
Williams et al. ⁵⁷	9.0	43.9	-	-
	8.0	42.9 ± 2.1	-	-

* standard error

The treadmill velocity of the male subjects is unusual in that no previous study has utilized the exact same speed. However, other investigations including female subjects have utilized the same workload. It can be seen that the male subjects' oxygen consumption is similar to what one would expect relative to small differences in velocity. However, the female subjects on average consumed less oxygen relative to previous studies.

Running economy is a variable measure, and is expected to vary up to 30% even in highly-trained runners (16, 31). In the current study, RE varied 15% in both the male and female subjects, indicating that the current subject group was less heterogeneous for RE than previous studies. In addition, standard deviation about the mean VO_2 was similar to values reported from other studies (Table 5.1). Thus, the variation in RE measurement from this study was not different from previous work. Using the standard deviations from previous work, a priori power calculations indicated that a sample size of 20 would be sufficient to detect differences in VO_2 of 2 ml/kg/min with a power of 80%. However, the standard deviations in RE from the current study are lower than previous work, thus even with a smaller sample size than originally planned, the ability to detect a practically relevant difference is preserved. The current study had 80% power to detect a change as small as 1.6 ml/kg/min with 15 subjects.

Mean VO_2 was calculated over the entire 20-minute running trial for each subject, thus VO_2 values from the first three minutes of the RE trial (one minute rest, walking, and accelerating to test speed) were eliminated from the analysis. Following precooling, there was no change in the mean VO_2 value. In the control condition, VO_2 for all subjects averaged 41.1 ml/kg/min compared to 41.3 ml/kg/min in the precooled trial. Clearly, the precooling protocol did not reduce the oxygen cost of running as hypothesized. Further, the lack of change in VO_2 is not due to a lack of statistical power.

Fifteen other studies utilizing an endurance exercise protocol have also measured VO_2 following cooling. Most authors have not reported a significant change in VO_2 following cooling (1, 5, 6, 12, 14, 18, 21, 22, 26, 27, 30, 32, 43, 47, 58) with the exception of Lee and Haymes (33). However, it is important to note that a number of these studies utilized an endurance cycling or triathlon protocol, which should be compared to the current study with caution (5, 7, 12, 14, 26, 27, 30, 32, 43, 47, 58). Of the five running endurance protocols, two authors utilized a time trial format in which the athletes freely chose the exercise workload (1, 6). Following cooling, these studies demonstrated an increase in

performance and exercise workload, thus VO_2 would be expected to either remain the same or increase when compared to the control condition.

Three studies utilizing an endurance running protocol have also held the exercise workload constant. Lee and Haymes reported reduced VO_2 following cooling during treadmill running at 82% of VO_{2max} . This reduction was significant for the initial 15 minutes of running when compared to the control trial. However, the mean reduction in this variable was not reported by the authors. Another study by Drust et al. (21) utilized an intermittent, soccer-specific protocol to determine metabolic changes in response to precooling. These authors found a slight increase in VO_2 following cooling (2.5 compared to 2.65 L/min), however this change was not statistically significant.

The study by Folland et al. (22) was most similar to the current investigation. These authors found significant changes in stride length and frequency in male runners in response to water immersion, but no change in RE. In effort to reduce within-subject variability the current study included male subjects with higher aerobic fitness (mean VO_{2max} 60.8 compared to 64.4 ml/kg/min) and had subjects complete two treadmill accommodation trials prior to the experimental trials. In addition, RE was measured over a longer duration (10 vs 20 minutes) than in the Folland et al. study. In response to precooling, heart rate (average reduction 8 bpm vs 6 bpm) and T_c (both 0.3°C) reductions were similar for both investigations. However, although the current study involved more highly-trained athletes and monitored RE for a longer duration, there was no change in RE in response to cool water immersion.

Thus, although multiple investigations have failed to detect a significant change in VO_2 following cooling, most studies were not specifically designed to monitor this variable. Only two previous studies provide VO_2 data in either one-minute (22) or five-minute (33) intervals. For the remaining studies, mean VO_2 values were calculated either by splitting the protocol into two halves or by averaging VO_2 over the entire exercise period. In addition, in an effort to reduce within-subject variability, the current study included highly-trained subjects that had completed over 40 minutes of treadmill accommodation. Although the

current study was designed specifically to monitor changes in VO_2 , there were no differences due to the precooling procedure.

Heart rate

Heart rate is often reduced as well as T_c in response to precooling. This response has been demonstrated in a number of previous investigations (6, 14, 18, 22, 26, 27, 37, 43, 47, 59). In the current study, heart rate was reduced by an average of five beats per minute (bpm) during the precooling trial, and the difference was similar during both the treatment portion and running portion of the trial. Post-hoc testing utilizing least significant differences revealed significant differences in heart rate at minute 30 and 40 of the precooling treatment and during most of the treadmill run (see Figure 4.6). While heart rate increased as the treadmill run progressed, this increase was not significantly different between conditions and averaged 18 bpm between minute 1 and minute 20 of the RE trials.

The reduction in heart rate was likely due to an increased central blood volume as a result of blood vessel vasoconstriction in the skin. Cool water exposure likely caused peripheral vasoconstriction which led to a reduction in blood flow to the skin. Consequently, central blood flow and stroke volume were increased whereas heart rate was reduced to maintain cardiac output. Raven et al. demonstrated an increase in stroke volume of 11% and a decrease in heart rate (8 bpm) following cooling with a water-perfused garment (44). Forearm bloodflow has been demonstrated to be undetectable following ten minutes of water immersion at 17.0°C but measurable within five minutes of exposure to warm water following the cooling procedure (45). Additionally, Cui and colleagues (17) have demonstrated greater maintenance of cardiac output following cooling during progressive lower body negative pressure (LVNP). During LVNP, cardiovascular variables such as stroke volume, cardiac output, and arterial pressure are reduced due to the reduction in venous return. Following cooling, the reduction in these variables is attenuated supporting a greater central blood volume when compared to the control condition. In sum, the results

from a variety of protocols investigating cooling support the hypothesis that cold exposure leads to peripheral vasoconstriction, an enhanced central blood volume, an increased stroke volume, and a reduction in heart rate to maintain cardiac output.

In comparison to previous literature, almost all studies investigating the effects of precooling have reported a reduction in heart rate. Since this a common finding, only results from studies utilizing an endurance running protocol will be discussed. Following cooling, heart rates have been reported to be between 9 and 11 bpm lower at exercise onset (1, 33). For the current study, heart rate was 11 bpm lower during the rest minute of the RE trial. Previous authors have reported mean heart rate values over the entire exercise period of 5 to 8 beats per minute lower in the precooled condition (6, 21, 22, 53, 59). In the current study, the mean reduction in heart rate over the RE trial was 5 bpm. Thus, the heart rate responses recorded in the current study are similar to previous research.

Minute ventilation

It has been demonstrated that the changes in V_E are positively correlated to changes in VO_2 during a constant workload (52). Thus, if V_E increases, VO_2 is also likely to increase causing a reduction in economy. Likewise, a lower V_E is likely to be related to an improved running economy. As a result of the water immersion, mean V_E for all subjects decreased 0.6 liters/minute when compared to the control condition (68.1 ± 0.2 vs 68.7 ± 0.2 L/min), although this difference was not statistically significant ($p = .095$).

Flexibility

Lower-body flexibility was assessed via sit and reach in which subjects reached as far as possible toward their toes without bending their knees. A score of 23 cm represented a distance equal to an individual's toes whereas a score above 23 cm would indicate reaching beyond their toes. The mean score prior to and following the control condition was 22.8 ± 10.4 and 23.0 ± 9.5 cm,

respectively. This difference in flexibility was non-significant. Mean sit and reach score prior to and following the precooled condition was 21.2 ± 9.9 and 20.0 ± 10.3 cm, respectively. This difference was again non-significant. Thus, although the cool water immersion reduced core temperature, lower-body flexibility as determined by sit and reach did not change.

To summarize the results from all subjects, precooling did induce a significant reduction in T_c and mean heart rate throughout the precooling trial. Mean VO_2 , V_E , and flexibility did not change significantly when compared to the control trial. Thus, although precooling has been demonstrated to be a potent enhancer of endurance running performance, these enhancements cannot be attributed to positive changes in RE.

Differential response to precooling between sexes

An additional goal of this study was to investigate whether responses to precooling were sex-specific. As exercise variables are susceptible to hormonal changes throughout the menstrual cycle (29), all female subjects were tested during the follicular phase when VO_2 , heart rate, and V_E values are lowest and RE is highest (56). Only T_c can be directly compared between male and female subjects since the treadmill workload was different for each group. However, differences between the precooled and control condition will be examined separately for each sex.

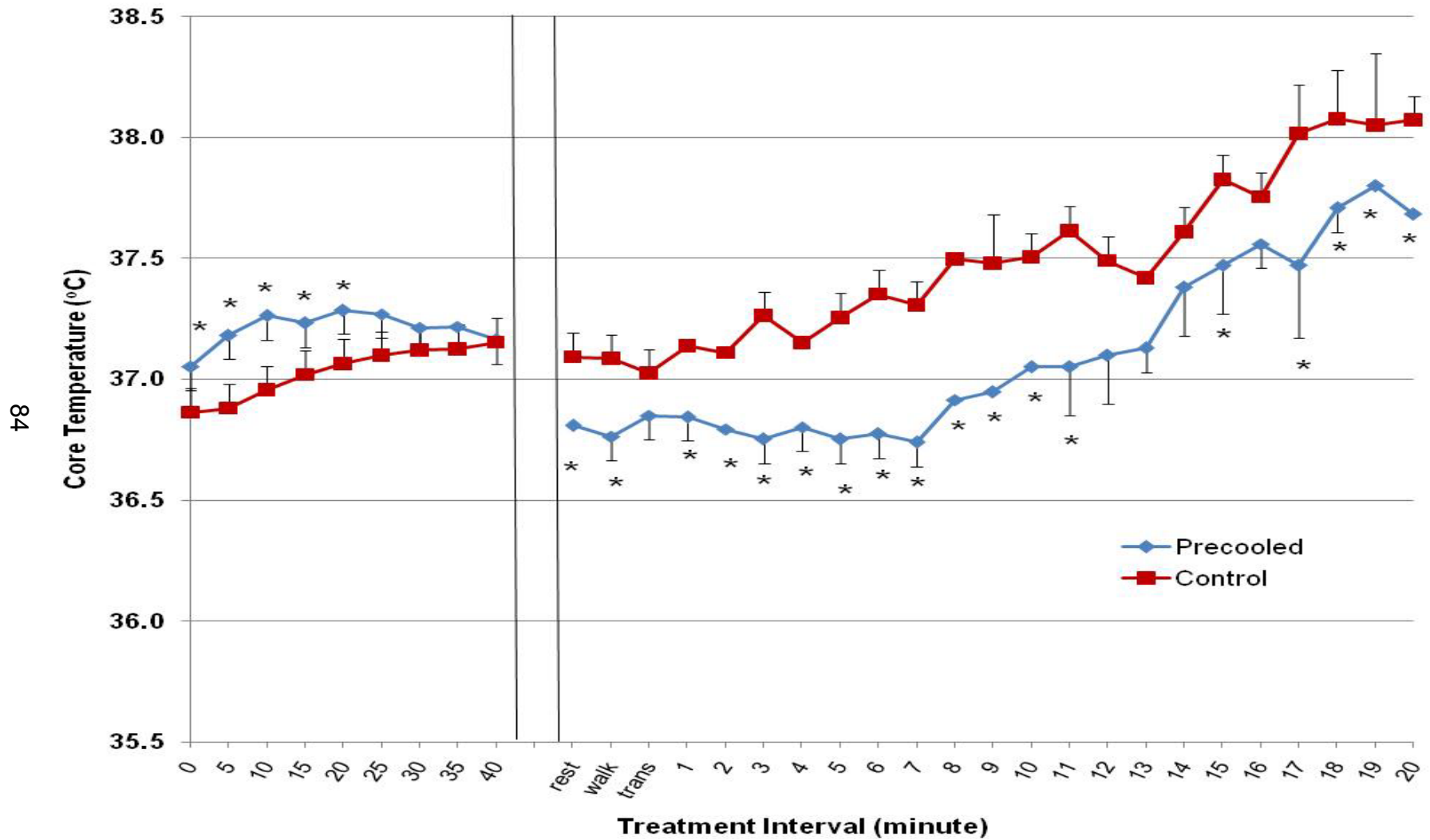
Core temperature

Precooling had a clear effect of reducing T_c when all subjects are considered, and this remains true when only the male or female subject group is examined. Figure 5.1 and Figure 5.2 describe the T_c response of the male and female groups, respectively, during both the precooled and control condition. It is important to note that some time points did not reach statistical significance possibly due to the lack of samples at that particular interval.

Mean T_c of the male subjects was significantly higher at baseline in the pre-cooled condition by 0.2°C and T_c remained elevated until minute 25 of the water immersion. This result is largely due to a lower mean T_c value in the control condition. Closer inspection of the T_c data from the male subjects revealed that six of the eight subjects had a lower T_c at the start of the control session on average by 0.33°C . Thus, a lower T_c was demonstrated by most of the male subjects, not just one or two subjects. There is no rationale to explain this result as the experimental trials were randomized and balanced evenly in the male subject group.

By the end of the control and precooling treatments, T_c was not significantly different. However, by the start of the RE trial, T_c was reduced on average by 0.3°C . The lowest mean T_c (36.65°C) occurred at minute 6 of the RE trial, during the third minute of running. Core temperature reached baseline values by minute 13, or during minute 10 of running. The total change in T_c from minimum to maximum (37.68°C) was just over 1.0°C . In the control condition, T_c increased from baseline values until the end of the treatment. By the start of the RE trial, T_c remained elevated above baseline. Total change in T_c during the exercise portion of the control trial was 0.98°C .

Figure 5.1: Mean core temperature of male subjects.



* significantly different from control condition $p < .05$

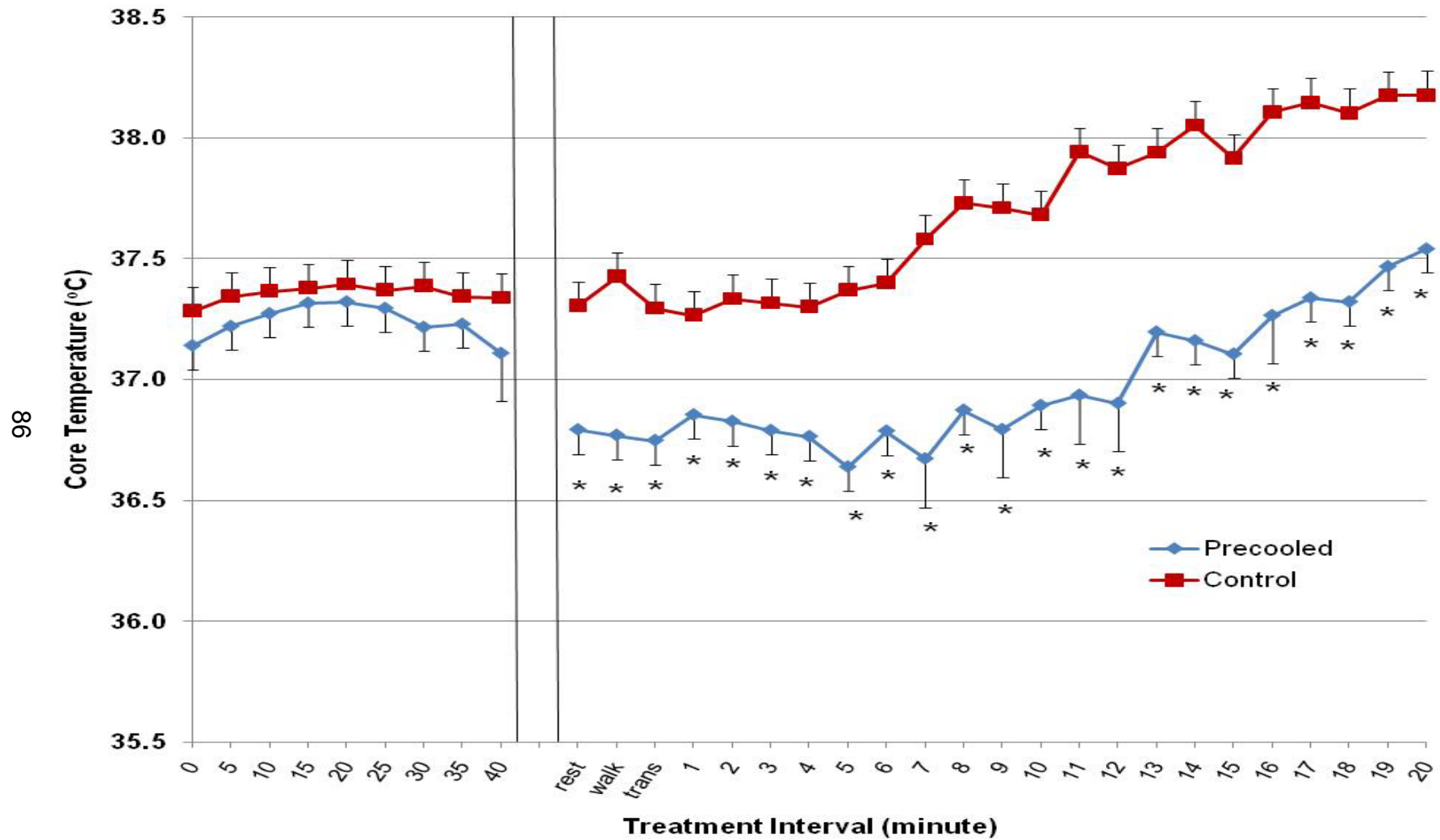
In contrast to the male subjects, the female subjects did not demonstrate a significant difference in T_c during the treatment portion. However, by the start of the treadmill run during the precooling trial, T_c had dropped on average 0.3°C . The lowest T_c (36.68°C) occurred at minute 5, or during minute 2 of running. Core temperature reached baseline values by minute 15, or by minute 12 of running. Total change in T_c during the exercise portion of the precooled and control trials was the same, 0.91°C .

Recall from Figure 4.2 in Chapter IV that the male subjects demonstrated a trend towards a reduced T_c during the control trial when compared to the female subjects. The mean reduction of 0.2°C persisted throughout the entire trial. This reduction in T_c was not present during the precooled condition. Thus, when the male and female subjects are directly compared based on T_c , male subjects tend to display lower T_c values during the control condition and not during the precooled condition.

When only the male responses from each trial are compared, T_c was higher during the precooling treatment when compared to the control. There were no differences when comparing the female responses only. Thus, the dramatic T_c differences between sexes seen during the control condition are due to a differential response of the male subjects.

While the lowest T_c in the precooling condition of both groups was similar, females displayed a greater average difference between trials. During the RE trial, T_c averaged 0.7°C higher in the control condition when compared to the precooled condition in the female subjects. The average difference for the male subjects over the same time frame was 0.4°C . Mean change in T_c during the treadmill run was similar between conditions for both groups. While the male subjects displayed a greater total change (1.0°C) when compared to the female subjects (0.91°C), they also ran at a higher workload.

Figure 5.2: Mean core temperature of female subjects.



* significantly different from control condition $p < .05$

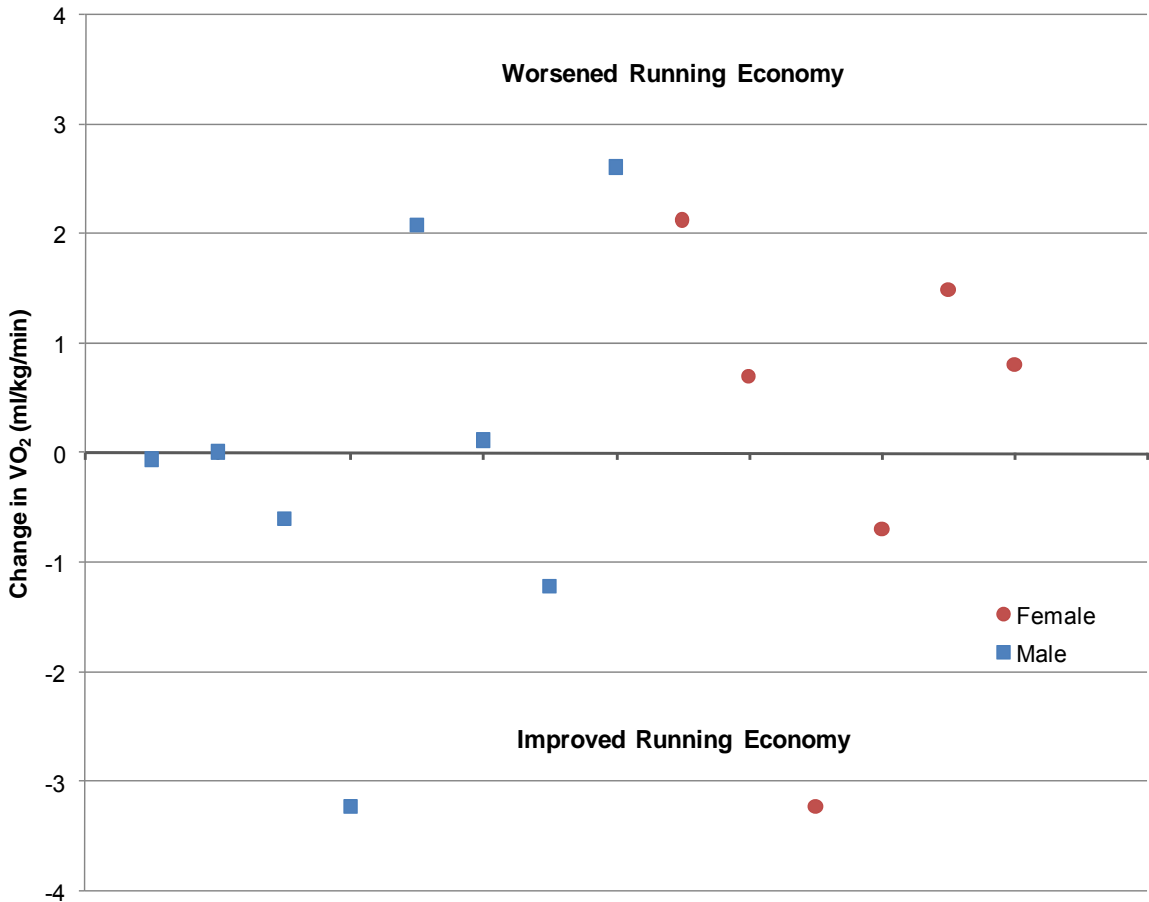
Thus, during the treatment phase, female subjects displayed no differences in T_c whereas the male subjects displayed a lower T_c during the control condition. The reduction in T_c due to the water immersion was almost identical between sexes, and the rate of increase in T_c was also similar. Thus, the apparent sex difference in average T_c between conditions is most likely due to a lower T_c in the male subjects during the control condition.

Oxygen consumption

In line with the analysis including all subjects, neither the male nor the female subject group displayed a significant change in VO_2 in response to the cool water immersion. The mean change for the male subjects was a non-significant decrease of 0.1 ml/kg/min. For the female subjects, mean VO_2 increased in the precooled condition by 0.2 ml/kg/min ($p = NS$). Figure 5.3 displays the individual responses of the 15 subjects who completed both trials. A negative change in VO_2 indicates that mean RE improved in the precooled condition for that subject. A positive change in VO_2 indicates that RE worsened in the precooled condition.

Nine out of 15 subjects demonstrated either a reduced economy or no change in economy following precooling. Further, there were no sex differences in VO_2 response.

Figure 5.3: Individual VO₂ responses in precooled condition compared to control.



Heart rate

The overall heart rate response due to the precooling treatment was a reduction in mean heart rate during the last ten minutes of the water immersion. Heart rate was also significantly reduced during the rest and walk minute on the treadmill and during most of the treadmill run. Separate analysis of heart rate for each sex revealed that the male subjects displayed a significantly lower heart rate for most of the precooling treatment (mean reduction = 7 bpm) beginning at baseline (min = 0) whereas the female subjects demonstrated little difference between treatments.

Both sexes displayed significantly lowered heart rate during the rest and walk minute on the RE trial. However, during the acceleration minute the female subjects had a mean increase in heart rate (11 beats per minute) above the control condition. This effect was largely due to the response of two female subjects in which the increase in heart rate from walking to accelerating up to test speed was 33 and 43 beats per minute greater in the precooled condition. During the remaining RE trial, heart rate was generally lower in the precooled condition and reached statistical significance at two other time points.

Minute ventilation

There was no main effect of the precooling procedure on V_E when all subjects are considered. This remains true for the male subjects, however the female subjects did display a mean reduction of 1.4 liters/min in V_E ($p = .000$) following water immersion. It is unknown what mechanism may have lead to a reduction in V_E in the female subjects only. However, one possible reason may be the greater T_c change demonstrated by the female subjects. Recall that the difference in T_c between the control and precooled trials averaged 0.4°C for the male subjects whereas this difference in the female subjects was much greater at 0.7°C . Perhaps the lack of a significance difference in V_E in the male subjects is due to a reduced T_c change between conditions, largely to due to an unusually low T_c at the onset of the control trial. A study by Hayashi et al. demonstrated a significant reduction in V_E following five minutes of cool water immersion between two exercise bouts (28). Male subjects cycled at 65% of $VO_{2\text{peak}}$ for 40 minutes, immersed their legs in 20°C or 35°C (control condition), and cycled again at 65% of $VO_{2\text{peak}}$ for 10 minutes. Following cooling, mean V_E was reduced by 3.1 liters/min for the first five minutes of the second exercise bout. In addition, T_{es} was 0.7°C lower in the cooled condition. Thus, the lack of a significant difference in V_E in the male subject group may be due to the modest T_c change experienced in this subject group.

Generally, V_E is associated with RE so that as V_E is reduced, so is oxygen cost (51). However, in this situation, V_E is reduced following cooling while the

mean oxygen cost of running has actually increased. Minute ventilation was reduced in four of the six female subjects, so this decrease is not due to the response of a single subject. Further, time of the menstrual cycle was standardized among the female subjects so this decrease in V_E cannot be attributed to a reduction in progesterone (29).

No study prior to this investigation has documented a significant reduction in V_E in response to precooling. Only two studies have reported measurement of this variable (21, 22), but there was no significant changes in V_E following cooling. In a soccer-specific treadmill protocol, V_E was reduced but the reduction was not statistically significant (21). In the Folland et al. study (22) in which RE was the variable of interest, mean V_E increased in the precooling condition, but this was also non-significant. In addition, female subjects were not included as part of either study group. Thus, the changes in V_E in this study appear to be sex-specific, with female subjects demonstrating a larger reduction in this variable when compared to male subjects. However, this may be due to the larger T_c difference between conditions demonstrated by the female subjects.

Flexibility

In general, the female subjects were more flexible than the male subjects at all time points. The mean female pretest score was 27.9 ± 6.6 cm compared to 17.8 ± 10.9 cm for the male subjects. Following the control condition, there was little change in the male subjects (0.06 cm decrease) and a slight increase in flexibility (0.54 cm) for the female subjects. Both of these changes were non-significant. Following water immersion, flexibility declined in the female subjects by 0.50 cm and by 2.78 cm in the male subjects. While there was a significant main effect of cooling for the male subjects, there was no time by treatment interaction. Thus, flexibility in the precooled condition was reduced at both time points when compared to the control.

To summarize the sex differences in response to precooling, it appears that men and women demonstrate a similar response to precooling with the exception of few variables. For example, T_c response during the precooling

treatment was similar, however the male subjects demonstrated a reduction in T_c during the control treatment when compared to the female subjects. The minimum T_c for both groups, which was almost identical, occurred only one minute apart during the treadmill run. Additionally, the rate of change in T_c was similar for both the precooled and control condition and between sexes.

Oxygen consumption did not vary in response to the precooling treatment, and neither group demonstrated a significant change compared to the control condition. Mean heart rate did not change during immersion for the female subjects, whereas the male subjects had a significant reduction of this variable. The female subjects demonstrated an unusual increase in heart rate during the precooled condition during the acceleration minute of the RE trial, however the heart rate response was lowered throughout the remainder of the treadmill run.

While the female subjects were more flexible than the male subjects at any given time, there was no sex difference in flexibility due to the water immersion. However, another major sex difference was demonstrated in V_E . On average, V_E decreased by 1.4 liters/minute in the female subjects following cooling. A reduction in this variable did not occur in the male subjects. Unfortunately, there is no explanation for this difference at the current time.

Correlation analyses

One of the main purposes for measuring RE is that this variable is strongly linked to running performance in highly-trained athletes. While a high VO_{2max} is required for elite runners, it is often differences in RE that determine race outcomes. Even in a group of highly-trained runners, RE will vary widely in spite of a narrow range of VO_{2max} values. Thus, it would be expected that the current group of athletes demonstrate little variability in VO_{2max} , but vary widely in RE and thus, ten kilometer performance. Correlational analysis between several outcome variables was performed to determine the link between VO_{2max} and ten kilometer run performance, and RE and ten kilometer run performance. In addition, the relationship between flexibility and oxygen cost while running was

determined and neither the male nor the female subjects demonstrated a significant correlation.

VO_{2max} and ten kilometer time

Figure 4.13 displays the relationship between VO_{2max} and ten kilometer time of the current subject group. The female subjects did display a significant correlation between these variables indicating that those runners with the highest VO_{2max} values also perform the best at the ten kilometer distance. Thus, the female athletes would be considered heterogeneous for VO_{2max}. This result would be expected in a group of runners with varying running abilities. However, the mean ten kilometer time of the female subjects was 42.6 ± 2.4 minutes, confirming that they are in fact well-trained and run the ten kilometer distance in a similar time. Thus, VO_{2max} varied even within a group of female runners with similar performances.

The male athletes, on the other hand, did not demonstrate a significant relationship between these variables. The VO_{2max} values of most of the male subjects fell within a narrow range (64 to 67.2 ml/kg/min) with the exception of one athlete (56.5 ml/kg/min). However, ten kilometer time was variable (31.33 to 38.98 minutes). Thus, the male subjects were in fact homogeneous for VO_{2max} as would be expected in a group of highly-trained runners.

Ten kilometer time and running economy

As demonstrated in the male subjects, running performance can vary widely even among a group of athletes homogenous for VO_{2max}. Other factors such as lactate threshold, running velocity at lactate threshold, and RE ultimately determine who turns their high aerobic power into top finishes. Running economy has been significantly linked to ten kilometer performance in previous studies (13, 38) however neither the male nor the female subjects demonstrated a significant relationship. A higher oxygen cost of running should be positively associated with slower running times. While the male subjects display this relationship in the expected direction, the correlation was non-significant ($p =$

.204). The female subjects not only displayed a non-significant correlation, but also displayed a negative relationship suggesting that the least economical runners were also the fastest runners. This result may be due to a low number of female subjects in the current study.

Flexibility and running economy

Multiple authors have demonstrated significant correlations between flexibility and RE (16, 23, 31) across a variety of subject groups and at multiple treadmill velocities. Those individuals with the least amount of flexibility tend to consume the least amount of oxygen and would be considered the most economical. In the current study, both the male and female subject groups demonstrated a positive correlation between flexibility, as determined by sit and reach score, and oxygen cost at the sex-specific speed. However, neither of these correlations were significant (male correlation $p = .726$, female correlation $p = .673$).

To summarize the results of the six correlations between outcome variables, only one correlation was in the anticipated direction. The non-significant relationship between VO_{2max} and ten kilometer time in the male subjects was expected among a group of highly-trained runners. None of the remaining correlations were significant as anticipated, and the correlation between VO_{2max} and ten kilometer time in the female subjects was unexpectedly significant.

Summary

To date, mechanisms to explain the dramatic improvements in endurance performance following precooling remain unknown. The purpose of this study was to determine if precooling improved RE in a group of highly-trained, treadmill-accommodated runners. Further, no study to date has attempted to determine any sex differences in response to precooling.

Results of the study indicate that the precooling protocol was effective in reducing T_c and heart rate in all subjects, however the reduction in flexibility was

not statistically significant. Comparison of the male and female subjects indicated a differential response among sexes in which the male subjects had an elevated T_c during the control treatment and the female subjects had a brief increase in heart rate during the acceleration minute of the precooling condition. Minute ventilation was reduced in the female group post-cooling, and this effect was not demonstrated in the male subjects. Correlational analyses did not support previous findings in which RE is significantly associated with running performance nor was flexibility significantly related to RE.

Thus, although precooling remains a potent enhancer of endurance performance, the results of the current study do not suggest that oxygen cost is reduced in the precooled state. The results of the sex comparisons do indicate a sex-specific response to precooling. Since no other study has compared sex responses, or standardized phase of the menstrual cycle, response to cooling and degree of performance enhancement in female subjects may be dependent on menstrual cycle phase.

Appendix 1

Consent to Participate in a Research Study

TITLE OF STUDY: PRECOOLING AND RUNNING ECONOMY

WHY ARE YOU BEING INVITED TO TAKE PART IN THIS RESEARCH?

You are being invited to take part in a research study about the influence of precooling on running economy. You are being invited to take part in this research study because you are a healthy runner and are between the ages of 18 and 45 years. In addition, you have run a 10K race faster than 40 minutes if you are male, or 45 minutes if you are female. If you volunteer to take part in this study, you will be one of about 50 people to do so.

WHO IS DOING THE STUDY?

The person in charge of this study is Molly Wilson (PI) of the University of Kentucky's Kinesiology & Health Promotion department. She is being guided in this research by JW Yates, PhD. There may be other people on the research team assisting at different times during the study.

WHAT IS THE PURPOSE OF THIS STUDY?

The purpose of this study is to investigate the impact of precooling (a lower body temperature) on running economy, or the energy required to run at a specific speed and grade. Previous studies in this area have been unclear as to how a lower temperature improves endurance performance. We hope to learn more about precooling and running economy by conducting this study.

WHERE IS THE STUDY GOING TO TAKE PLACE AND HOW LONG WILL IT LAST?

The research procedures will be conducted at the Exercise Physiology Lab in the Seaton Center on the Lexington campus of the University of Kentucky. You will need to come to the Seaton Center four times during the study. Each visit will take about one and half hours. You will be asked to wear the same shorts and shoes each time. The total amount of time you will be asked to volunteer for this study is approximately six hours over the next four months.

WHAT WILL YOU BE ASKED TO DO?

You will be required to come to the Exercise Physiology Lab on four separate occasions.

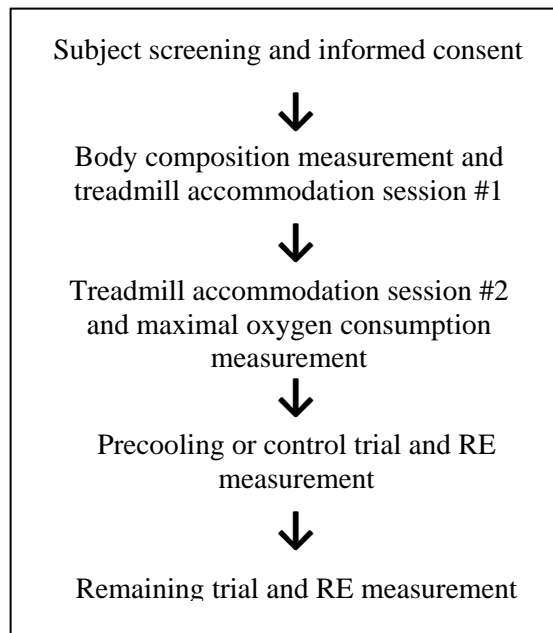
During your first visit, we will ask you a few questions about your health history using a form called the Physical Activity Readiness Questionnaire. We will ask you to sign this form and will provide you with a copy if you want one. We will also ask you questions about your history of lower body injury, intestinal disorder or surgery, training history, and questions regarding your menstrual cycle and contraceptive use if you are female. You will also be asked to provide race results indicating when you attained the performance standard. You will then be weighed and measured for height before entering the underwater weighing tank to determine your body composition. Once seated inside the tank you will exhale as much air as possible and then submerge your body underwater. At this point the investigator will measure your weight. A series of equations will be applied to estimate your body fat percentage.

You will be asked to complete two familiarization trials to allow you to adjust your running style to the treadmill. Prior to the first familiarization trial your blood pressure will be taken three times, once at rest and twice while walking at a moderate pace on the treadmill. During these trials, you will run for approximately 20 minutes at the same speed on a level grade. During familiarization sessions, we will measure your oxygen intake using a mouthpiece and plastic tubing connected to a computer. A noseclip will also be used to prevent breathing through your nose. Following the second familiarization trial, you will complete a maximal oxygen consumption test. This test will also be performed on the treadmill with the same equipment used to monitor oxygen intake during the familiarization trials. You will begin the test by completing two walking stages. During the third stage, the treadmill speed will be increased until you are at a comfortable running pace. The grade of the treadmill will gradually increase until you feel you can no longer continue. At this point the test will end, and you will be asked to walk slowly on the treadmill until you have recovered.

Approximately one hour prior to your arrival for your third session, you will be asked to swallow a temperature sensor. This sensor is approximately the size of a large vitamin and will be passed approximately 18 and 30 hours after you swallow it. Once you arrive at the lab, we will measure lower body flexibility using the sit-and-reach test. Next, you will enter the underwater weighing tank where you will rest for approximately forty minutes. The water temperature will be cool, but should not cause you to shiver. Following cooling, you will repeat the sit-and-reach test and run on the treadmill just as you did in the familiarization trials.

Prior to the fourth and final session, you will again be asked to swallow another temperature sensor. Upon arrival to the lab you will perform another sit-and-reach test, rest for forty minutes, and perform a second sit-and-reach test. You will be asked to run on the treadmill as during the previous sessions. On the day before the third and fourth laboratory sessions you will be asked to refrain from intense weight training and high-intensity running and cycling workouts. You will also be asked to refrain from all exercise prior to the laboratory sessions on day three and four.

Figure 1: Diagram of Testing Procedures



Following both day three and four the investigator, Molly Wilson, will contact you by email to confirm that you have passed the temperature sensor. If you do not respond to the email, she will contact you via telephone. If you have not passed the sensor within 48 hours of swallowing it you will be asked to return to the lab. If the sensor is still detected at this point in time you will be advised to see your physician.

ARE THERE REASONS WHY YOU SHOULD NOT TAKE PART IN THIS STUDY?

Some studies have suggested that running abilities are different in well-trained athletes when compared to untrained individuals. If you are not currently training or have not met the running standards, you will not be allowed to take part in this study. Because this study involves testing of your lower body, you should not participate if you have suffered a serious lower body injury within the last six months. If you have a history of an intestinal, respiratory, or cardiovascular disorder, intestinal surgery, weigh less than eighty pounds, and are not between 18 and 45 years old, you will not be allowed to participate. Female subjects who are using progesterone-based contraceptives continuously will also not be allowed to participate.

WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?

Muscle cramps, muscle fatigue, dizziness, orthopedic injury, cardiorespiratory distress, and even death are all possible outcomes of any high intensity physical activity, including that required for this study. However, in this monitored situation, the risks are lower than when exercising at this level on your own. The mouthpiece and noseclips may be

uncomfortable, as may the heart rate monitor, which could cause skin irritation. One less likely risk is abdominal discomfort due to the temperature sensor. It is expected that you will pass the sensor 18 to 30 hours after you swallow it. You may require surgery if the sensor becomes trapped in your intestines, however the likelihood of this occurring is extremely low. Exposure to cool water may also be uncomfortable

There is always a chance that any physical activity can harm you, and the activity in this study is no different. We will do everything we can to keep you from being harmed. In addition to the risks listed above, you may experience a previously unknown risk or side effect.

WILL YOU BENEFIT FROM TAKING PART IN THIS STUDY?

As a participant in this study you will gain valuable knowledge about your aerobic fitness and body composition, tests which would normally cost you \$200 and \$50, respectively.

DO YOU HAVE TO TAKE PART IN THE STUDY?

If you decide to take part in the study, it should be because you really want to volunteer. You will not lose any benefits or rights you would normally have if you choose not to volunteer. You can stop at any time during the study and still keep the benefits and rights you had before volunteering.

IF YOU DON'T WANT TO TAKE PART IN THE STUDY, ARE THERE OTHER CHOICES?

If you do not want to be in the study, there are no other choices except not to take part in the study.

WHAT WILL IT COST YOU TO PARTICIPATE?

There is no cost to you associated with participation. The University of Kentucky is not allowed to bill your insurance company, Medicare, or Medicaid for the medical costs of procedures done strictly for research.

WHO WILL SEE THE INFORMATION THAT YOU GIVE?

We will keep private all research records that identify you to the extent allowed by law. Officials of the Food and Drug Administration (FDA) and the University of Kentucky (UK) may look at or copy pertinent portions of records that identify you.

Your information will be combined with information from other people taking part in the study. When we write about the study to share it with other researchers, we will write about the combined information we have gathered. You will not be identified in these written materials.

We may publish the results of this study; however, we will keep your name and other identifying information private.

We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information, or what that information is. For example, your name will be kept separate from the information you give, and these two things will be stored in different places under lock and key.

CAN YOUR TAKING PART IN THE STUDY END EARLY?

If you decide to take part in the study you still have the right to decide at any time that you no longer want to continue. You will not be treated differently if you decide to stop taking part in the study.

The individuals conducting the study may need to withdraw you from the study. This may occur if you are not able to follow the directions they give you or if they find that your being in the study is more risk than benefit to you.

There are no expected adverse effects to you if you do not complete this study.

WHAT HAPPENS IF YOU GET HURT OR SICK DURING THE STUDY?

If you believe you are hurt or if you get sick because of something that is done during the study, you should call Molly Wilson at (859) 230-3023 or the faculty advisor, J.W. Yates, Ph.D. at (859) 257-5879 immediately. It is important for you to understand that the University of Kentucky will not pay for the cost of any care or treatment that might be necessary because you get hurt or sick while taking part in this study. That cost will be your responsibility. Also, the University of Kentucky will not pay for any wages you may lose if you are harmed by this study.

Medical costs that result from research-related harm can not be included as regular medical costs. The University of Kentucky is not allowed to bill your insurance company. You should ask your insurer if you have any questions about your insurer's willingness to pay under these circumstances. Therefore, the costs related to your care and treatment because of something that is done during the study will be your responsibility.

WILL YOU RECEIVE ANY REWARDS FOR TAKING PART IN THIS STUDY?

You will not receive any rewards or payment for taking part in the study.

WHAT IF YOU HAVE QUESTIONS?

Before you decide whether to accept this invitation to take part in the study, please ask any questions that might come to mind now. Later, if you have questions about the study, you can contact the investigator, Molly Wilson at (859) 230-3023 or the faculty advisor, J.W. Yates, Ph.D. at (859) 257-5879. If you have any questions about your rights as a

volunteer in this research, contact the staff in the Office of Research Integrity at the University of Kentucky at 859-257-9428 or toll free at 1-866-400-9428. We will give you a copy of this consent form to take with you.

WHAT ELSE DO YOU NEED TO KNOW?

The University of Kentucky Kinesiology and Health Promotion department is providing financial support and/or material for this study.

You will be told if any new information is learned which may affect your condition or influence your willingness to continue taking part in this study.

Signature of person agreeing to take part in the study

Date

Printed name of person agreeing to take part in the study

Name of person providing information to subject

Date

Signature of Investigator

Appendix 2

Physical Activity Readiness Questionnaire (PAR-Q)

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
<input type="checkbox"/>	<input type="checkbox"/>	1. Has your doctor ever said that you have a heart condition <u>and</u> that you should only do physical activity recommended by a doctor?
<input type="checkbox"/>	<input type="checkbox"/>	2. Do you feel pain in your chest when you do physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	3. In the past month, have you had chest pain when you were not doing physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	4. Do you lose your balance because of dizziness or do you ever lose consciousness?
<input type="checkbox"/>	<input type="checkbox"/>	5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
<input type="checkbox"/>	<input type="checkbox"/>	7. Do you know of <u>any other reason</u> why you should not do physical activity?

If
you
answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active — begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal — this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever — wait until you feel better; or
- if you are or may be pregnant — talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME _____

SIGNATURE _____

DATE _____

SIGNATURE OF PARENT
or GUARDIAN (for participants under the age of majority) _____

WITNESS _____

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.



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Appendix 3

Health, Training, and Injury History Questionnaire

Name: _____

Date: _____

Investigator: _____

Please answer the following questions

1. Have you ever experienced a major injury to your lower body (such as a broken bone or torn ligament) that affects your running? Y N

If yes, please explain

2. Do you experience pain in your lower body on a regular basis that affects your running? Y N

If yes, please explain

4. Have you ever been diagnosed with a heart condition? Y N

If yes, please explain

5. Have you ever been diagnosed with a respiratory condition such as asthma? Y N

If yes, please explain

6. Have you ever been diagnosed with an intestinal disorder (such as diverticulitis or inflammatory bowel disease)? Y N

If yes, please explain

7. Have you ever had intestinal surgery? Y N

If yes, please explain

8. Do you have a pacemaker or any other implanted electrical device? Y N

If yes, please explain

9. Do you currently smoke or have you smoked regularly within the last 6 months? Y N

10. On average, how many times per week you engage in run training? _____ times per week

11. How long have you been engaged in run training? _____ years

12. Please provide the results of your last three races (running or triathlon events only please)

Race Date	Race Type	Run Distance	Time (or Run Split)
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____

13. Please provide the following information for your next three planned races (running and triathlon events only please)

Race Date	Race Type	Run Distance
_____	_____	_____
_____	_____	_____
_____	_____	_____

14. When did you achieve the study criterion and what was your time?

Name of Event _____

Distance _____

Finish Time _____

For Female Subjects Only

15. When was the date of your last menstrual cycle? _____

16. How many menstrual cycles have you had in the last 12 months? _____

17. On average, how many days is your menstrual cycle? _____

18. Are you currently taking oral contraceptives? Y N
If yes, which brand do you take? _____

19. Are you using any other form of birth control (such as a patch)? Y N
If yes, please describe _____
If yes, which brand do you use? _____

References

1. Arngrimsson, S. A., D. S. Petitt, M. G. Stueck, D. K. Jorgensen, and K. J. Cureton. Cooling vest worn during active warm-up improves 5-km run performance in the heat. *J Appl Physiol.* 96:1867-1874, 2004.
2. Bergh, U. and B. Ekblom. Physical performance and peak aerobic power at different body temperatures. *J Appl Physiol.* 46:885-889, 1979.
3. Blomstrand, E., U. Bergh, B. Essen-Gustavsson, and B. Ekblom. Influence of low muscle temperature on muscle metabolism during intense dynamic exercise. *Acta Physiol Scand.* 120:229-236, 1984.
4. Bolster, D. R., S. W. Trappe, K. R. Short, M. Scheffield-Moore, A. C. Parcell, K. M. Schulze, and D. L. Costill. Effects of precooling on thermoregulation during subsequent exercise. *Med Sci Sports Exerc.* 31:251-257, 1999.
5. Bolster, D. R. a. A., L.E. Exercise, thermoregulation, and precooling. *American Journal of Medicine and Sports.* 2:155-164, 2000.
6. Booth, J., F. Marino, and J. J. Ward. Improved running performance in hot humid conditions following whole body precooling. *Med Sci Sports Exerc.* 29:943-949, 1997.
7. Booth, J., B. R. Wilsmore, A. D. Macdonald, A. Zeyl, S. McGhee, D. Calvert, F. E. Marino, L. H. Storlien, and N. A. Taylor. Whole-body pre-cooling does not alter human muscle metabolism during sub-maximal exercise in the heat. *Eur J Appl Physiol.* 84:587-590, 2001.
8. Bransford, D. R. and E. T. Howley. Oxygen cost of running in trained and untrained men and women. *Med Sci Sports.* 9:41-44, 1977.
9. Brozek, J. and A. Henschel. *Techniques for measuring body composition; proceedings of a conference, Quartermaster Research and Engineering Center, Natick, Massachusetts, January 22-23, 1959.* Washington, D.C.: National Academy of Sciences-National Research Council, 1961
10. Castle, P. C., A. L. Macdonald, A. Philp, A. Webborn, P. W. Watt, and N. S. Maxwell. Precooling leg muscle improves intermittent sprint exercise performance in hot, humid conditions. *J Appl Physiol.* 100:1377-1384, 2006.
11. Cavanagh, P. R. and K. R. Williams. The effect of stride length variation on oxygen uptake during distance running. *Med Sci Sports Exerc.* 14:30-35, 1982.

12. Cheung, S. and A. Robinson. The influence of upper-body pre-cooling on repeated sprint performance in moderate ambient temperatures. *J Sports Sci.* 22:605-612, 2004.
13. Conley, D. L. and G. S. Krahenbuhl. Running economy and distance running performance of highly trained athletes. *Med Sci Sports Exerc.* 12:357-360, 1980.
14. Cotter, J. D., G. G. Sleivert, W. S. Roberts, and M. A. Febbraio. Effect of pre-cooling, with and without thigh cooling, on strain and endurance exercise performance in the heat. *Comp Biochem Physiol A Mol Integr Physiol.* 128:667-677, 2001.
15. Coyne, M. D., C. M. Kesick, T. J. Doherty, M. A. Kolka, and L. A. Stephenson. Circadian rhythm changes in core temperature over the menstrual cycle: method for noninvasive monitoring. *Am J Physiol Regul Integr Comp Physiol.* 279:R1316-1320, 2000.
16. Craib, M. W., V. A. Mitchell, K. B. Fields, T. R. Cooper, R. Hopewell, and D. W. Morgan. The association between flexibility and running economy in sub-elite male distance runners. *Med Sci Sports Exerc.* 28:737-743, 1996.
17. Cui, J., S. Durand, B. D. Levine, and C. G. Crandall. Effect of skin surface cooling on central venous pressure during orthostatic challenge. *Am J Physiol Heart Circ Physiol.* 289:H2429-2433, 2005.
18. Daanen, H. A., E. M. van Es, and J. L. de Graaf. Heat strain and gross efficiency during endurance exercise after lower, upper, or whole body precooling in the heat. *Int J Sports Med.* 27:379-388, 2006.
19. Daniels, J. and N. Daniels. Running economy of elite male and elite female runners. *Med Sci Sports Exerc.* 24:483-489, 1992.
20. Davies, M. J., M. T. Mahar, and L. N. Cunningham. Running economy: comparison of body mass adjustment methods. *Res Q Exerc Sport.* 68:177-181, 1997.
21. Drust, B., N. T. Cable, and T. Reilly. Investigation of the effects of the pre-cooling on the physiological responses to soccer-specific intermittent exercise. *Eur J Appl Physiol.* 81:11-17, 2000.
22. Folland, J. P., D. S. Rowlands, R. Thorp, and A. Walmsley. Leg heating and cooling influences running stride parameters but not running economy. *Int J Sports Med.* 27:771-779, 2006.
23. Gleim, G. W., N. S. Stachenfeld, and J. A. Nicholas. The influence of flexibility on the economy of walking and jogging. *J Orthop Res.* 8:814-823, 1990.

24. Godges, J. J., P. G. MacRae, and K. A. Engelke. Effects of exercise on hip range of motion, trunk muscle performance, and gait economy. *Phys Ther.* 73:468-477, 1993.
25. Gonzalez-Alonso, J., C. Teller, S. L. Andersen, F. B. Jensen, T. Hyldig, and B. Nielsen. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *J Appl Physiol.* 86:1032-1039, 1999.
26. Hasegawa, H., T. Takatori, T. Komura, and M. Yamasaki. Combined effects of pre-cooling and water ingestion on thermoregulation and physical capacity during exercise in a hot environment. *J Sports Sci.* 24:3-9, 2006.
27. Hasegawa, H., T. Takatori, T. Komura, and M. Yamasaki. Wearing a cooling jacket during exercise reduces thermal strain and improves endurance exercise performance in a warm environment. *J Strength Cond Res.* 19:122-128, 2005.
28. Hayashi, K., Y. Honda, T. Ogawa, H. Wada, N. Kondo, and T. Nishiyasu. Effects of brief leg cooling after moderate exercise on cardiorespiratory responses to subsequent exercise in the heat. *Eur J Appl Physiol.* 92:414-420, 2004.
29. Hessemer, V. and K. Bruck. Influence of menstrual cycle on thermoregulatory, metabolic, and heart rate responses to exercise at night. *J Appl Physiol.* 59:1911-1917, 1985.
30. Hessemer, V., D. Langusch, L. K. Bruck, R. H. Bodeker, and T. Breidenbach. Effect of slightly lowered body temperatures on endurance performance in humans. *J Appl Physiol.* 57:1731-1737, 1984.
31. Jones, A. M. Running economy is negatively related to sit-and-reach test performance in international-standard distance runners. *Int J Sports Med.* 23:40-43, 2002.
32. Kay, D., D. R. Taaffe, and F. E. Marino. Whole-body pre-cooling and heat storage during self-paced cycling performance in warm humid conditions. *J Sports Sci.* 17:937-944, 1999.
33. Lee, D. T. and E. M. Haymes. Exercise duration and thermoregulatory responses after whole body precooling. *J Appl Physiol.* 79:1971-1976, 1995.
34. MacDougall, J. D., W. G. Reddan, C. R. Layton, and J. A. Dempsey. Effects of metabolic hyperthermia on performance during heavy prolonged exercise. *J Appl Physiol.* 36:538-544, 1974.

35. Marino, F. E. Methods, advantages, and limitations of body cooling for exercise performance. *Br J Sports Med.* 36:89-94, 2002.
36. Marsh, D. and G. Sleivert. Effect of precooling on high intensity cycling performance. *Br J Sports Med.* 33:393-397, 1999.
37. Mitchell, J. B., B. K. McFarlin, and J. P. Dugas. The effect of pre-exercise cooling on high intensity running performance in the heat. *Int J Sports Med.* 24:118-124, 2003.
38. Morgan, D. W., F. D. Baldini, P. E. Martin, and W. M. Kohrt. Ten kilometer performance and predicted velocity at VO₂max among well-trained male runners. *Med Sci Sports Exerc.* 21:78-83, 1989.
39. Morgan, D. W. and M. Craib. Physiological aspects of running economy. *Med Sci Sports Exerc.* 24:456-461, 1992.
40. Morgan, D. W., M. W. Craib, G. S. Krahenbuhl, K. Woodall, S. Jordan, K. Filarski, C. Burleson, and T. Williams. Daily variability in running economy among well-trained male and female distance runners. *Res Q Exerc Sport.* 65:72-77, 1994.
41. Morgan, D. W., P. E. Martin, G. S. Krahenbuhl, and F. D. Baldini. Variability in running economy and mechanics among trained male runners. *Med Sci Sports Exerc.* 23:378-383, 1991.
42. Nelson, A. G., J. Kokkonen, C. Eldredge, A. Cornwell, and E. Glickman-Weiss. Chronic stretching and running economy. *Scand J Med Sci Sports.* 11:260-265, 2001.
43. Olschewski, H. and K. Bruck. Thermoregulatory, cardiovascular, and muscular factors related to exercise after precooling. *J Appl Physiol.* 64:803-811, 1988.
44. Raven, P. B., G. Pape, W. F. Taylor, F. A. Gaffney, and C. G. Blomqvist. Hemodynamic changes during whole body surface cooling and lower body negative pressure. *Aviat Space Environ Med.* 52:387-391, 1981.
45. Savard, G. K., K. E. Cooper, W. L. Veale, and T. J. Malkinson. Peripheral blood flow during rewarming from mild hypothermia in humans. *J Appl Physiol.* 58:4-13, 1985.
46. Schieb, D. A. Kinematic accomodation of novice treadmill runners. *Res Q Exerc Sport.* 57:1-7, 1986.
47. Schmidt, V. and K. Bruck. Effect of a precooling maneuver on body temperature and exercise performance. *J Appl Physiol.* 50:772-778, 1981.

48. Schniepp, J., T. S. Campbell, K. L. Powell, and D. M. Pincivero. The effects of cold-water immersion on power output and heart rate in elite cyclists. *J Strength Cond Res.* 16:561-566, 2002.
49. Sleivert, G. G., J. D. Cotter, W. S. Roberts, and M. A. Febbraio. The influence of whole-body vs. torso pre-cooling on physiological strain and performance of high-intensity exercise in the heat. *Comp Biochem Physiol A Mol Integr Physiol.* 128:657-666, 2001.
50. Stachenfeld, N. S., C. Silva, and D. L. Keefe. Estrogen modifies the temperature effects of progesterone. *J Appl Physiol.* 88:1643-1649, 2000.
51. Thomas, D. Q., Fernhall, B., and H. Granat. Changes in running economy during a 5-km run in trained men and women runners. *J Strength Cond.* 13:162-167, 1999.
52. Thomas, D. Q., Fernhall, B., Blanpeid, P., and K. Stillwell. Changes in running economy and mechanics during a submaximal 5-km run. *J Strength Cond.* 9:170-175, 1995.
53. Uckert, S. and W. Joch. Effects of warm-up and precooling on the endurance performance in the heat. *Br J Sports Med*, 2007.
54. Webster, J., E. J. Holland, G. Sleivert, R. M. Laing, and B. E. Niven. A light-weight cooling vest enhances performance of athletes in the heat. *Ergonomics.* 48:821-837, 2005.
55. Williams, K. R. and P. R. Cavanagh. Relationship between distance running mechanics, running economy, and performance. *J Appl Physiol.* 63:1236-1245, 1987.
56. Williams, T. J. Menstrual cycle phase and running economy. Arizona State University 1992.
57. Williams, T. J., G. S. Krahenbuhl, and D. W. Morgan. Daily variation in running economy of moderately trained male runners. *Med Sci Sports Exerc.* 23:944-948, 1991.
58. Wilson, T. E., S. C. Johnson, J. H. Petajan, S. L. Davis, E. Gappmaier, M. J. Luetkemeier, and A. T. White. Thermal regulatory responses to submaximal cycling following lower-body cooling in humans. *Eur J Appl Physiol.* 88:67-75, 2002.
59. Yeargin, S. W., D. J. Casa, J. M. McClung, J. C. Knight, J. C. Healey, P. J. Goss, W. R. Harvard, and G. R. Hipp. Body cooling between two bouts of exercise in the heat enhances subsequent performance. *J Strength Cond Res.* 20:383-389, 2006.

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Wilson, M. Aquatic plyometrics and the freestyle flip turn. Unpublished master's thesis, University of Louisville, Louisville, KY. 2003.

PUBLISHED ABSTRACTS:

Wilson, M. Moderate static stretching does not influence torque production of the knee flexors. *Medicine and Science in Sports and Exercise*, 38(5): S280.

Wilson, M. Aquatic plyometrics and the freestyle flipturn. *Medicine and Science in Sports and Exercise*, 36(5): S206.

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