Tissue Temperature Transients in Resting Contra-Lateral Leg Muscle Tissue During Isolated Knee Extension

Glen P. Kenny, Frank D. Reardon, Michel B. Ducharme, Mark L. Reardon, and Wytek Zaleski

Catalog Data

Key words: heat load, thermoregulation, hyperthermia

Abstract/Résumé
This study was designed to evaluate the role of non-active tissue in the retention and dissipation of heat during and following intense isolated muscle activity. Six subjects performed an incremental isotonic test (constant angular velocity, increases in force output) on a KIN-COM isokinetic apparatus to determine their maximal oxygen consumption during single knee extensions ($V\cdot O_{2sp}$). In a subsequent session, a thin wire multi-sensor temperature probe was inserted into the left vastus medialis under ultrasound guidance at a specific internal marker. The deepest temperature sensor (tip, $T_{mu10}$) was located ~10 mm from the femur and deep femoral artery with 2 additional sensors located at 15 ($T_{mu25}$) and 30 ($T_{mu40}$) mm from the tip. Implant site was midway between and medial to a line joining the anterior superior iliac spine and base of patella. Esophageal temperature ($T_{es}$) temperature was measured as an index of core temperature. Subjects rested in a supine position for 60 min followed by 30 min of seated rest in an ambient condition of 22 °C. Subjects then performed 15 min of isolated single right knee extensions against a dynamic resistance on a KIN COM corresponding to 60% of $V\cdot O_{2sp}$ at 60° · sec⁻¹. Exercise was followed by 60 min of seated rest. Resting $T_{es}$ was 37 °C while $T_{mu10}$, $T_{mu25}$, and $T_{mu40}$ were 36.58, 36.55 and 36.45 °C, respectively. Exercise resulted in a $T_{es}$ increase of 0.31 °C above pre-exercise resting. $T_{mu}$ of the

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non-exercising leg increased 0.23, 0.19 and 0.09 °C for \( T_{\mu 10} \), \( T_{\mu 25} \), and \( T_{\mu 40} \), respectively. While \( T_e \) decreased to baseline values within ~15 min of end-exercise, \( T_{\mu 10} \) reached resting values following ~40 min of recovery. These results suggest that during isolated muscle activity, convective heat transfer by the blood to non-active muscle tissue may have a significant role in maintaining resting core temperature.

L’objectif de cette étude est d’analyser le rôle des tissus inactifs dans la rétention et la dissipation de la chaleur durant et après une activité intense d’un muscle isolé. Six sujets participent à un test isotonique progressif (vitesse angulaire constante, augmentation de la production de force) sur un appareil isokinétique de marque KIN-COM ; la consommation maximale d’oxygène au cours d’extensions répétées du genou \( (\text{VO}_2_{\text{sp}}) \) est alors établie. Au cours d’une séance ultérieure, une mince sonde, munie de multiples capteurs sensibles à la chaleur, est insérée dans le vastus médialis gauche jusqu’à un marqueur interne identifié par échographie. Le capteur le plus enfoncé (pointe, \( T_{\mu 10} \)) se situe à ~10 mm du fémur et de l’artère fémorale profonde et les deux autres capteurs sont à 15 mm (\( T_{\mu 25} \)) et à 30 mm (\( T_{\mu 40} \)) de la pointe. La zone d’insertion est à mi-chemin et du côté médian d’une ligne reliant l’épine iliaque antéro-supérieure et la base de la rotule. La température œsophagienne \( (T_o) \) est mesurée afin d’obtenir un indicateur de la température du noyau. Les sujets sont au repos couché durant 60 min puis au repos assis durant 30 min dans un local dont la température ambiante est de 22 °C. Par la suite, les sujets exécutent durant 15 min des extensions du genou droit contre une résistance dynamique équivalent à 60 % du \( **\text{VO}_2_{\text{sp}} \) à une vitesse angulaire de 60° · s\(^{-1}\). L’exercice est suivi d’un repos assis de 60 min. La \( T_r \) de repos est de 37 °C et les \( T_{\mu 10} \), \( T_{\mu 25} \) et \( T_{\mu 40} \) sont de 36,58, 36,55 et 36,45 °C respectivement. La \( T_r \) augmente de 0,31 °C à cause de l’exercice et les \( T_{\mu 10} \), \( T_{\mu 25} \) et \( T_{\mu 40} \) du muscle inactif augmentent de 0,23, 0,19 et de 0,09 °C respectivement. La \( T_r \) reprend sa valeur de base ~15 min après la fin de l’exercice, mais \( T_{\mu 10} \) reprend sa valeur de repos ~40 min après. Ces observations indiquent qu’au cours d’une activité musculaire isolée, le transfert de la chaleur par la circulation sanguine aux muscles inactifs semble jouer un rôle important dans le maintien de la température du noyau.

Introduction

A number of studies have investigated the effect of thermal stress on the temperature profile of muscle tissue during rest and exercise. Early studies focused mainly on the possible relationships between changes in muscle temperature and the capacity for work, the effect of exogenous heating prior to exercise (Asmussen and Boje, 1945) and muscle blood flow distribution at rest (Barcroft and Edholm, 1946). Subsequent studies focused primarily on tissue temperature transients and heat loss responses during exercise (Aikas et al., 1962; Nadel et al., 1972; Saltin and Hermansen, 1966; Saltin et al., 1968, 1970, 1972).

To our knowledge, the study by Saltin et al. (1970) is one of the few studies that measured intramuscular leg temperature following low to intense exercise (25-75% \( \text{VO}_2_{\text{max}} \)) performed in a range of ambient temperatures (10 to 30 °C). Although they graphically represented quadriceps muscle temperature changes during post-exercise rest, they did not specifically address the post-exercise period. Their data demonstrates that post-exercise core and muscle temperatures decreased progressively during recovery to pre-exercise resting values within 10–15 min (except following intense exercise at 30 °C). In contrast, it has been shown
that esophageal temperature remains significantly elevated above baseline for at least 65 min after exercise (Thoden et al., 1994). Thoden and co-workers proposed that the reduction in forearm skin blood flow (SkBF) and mean skin temperature (except over the exercised muscle), despite a sustained increase in the post-exercise esophageal temperature, was consistent with a sustained post exercise increase in the threshold for cutaneous vasodilation. Kenny et al. (2000) provided evidence to support this observation by showing that exercise induces a residual effect on post exercise SkBF by increasing the post-exercise resting threshold for cutaneous vasodilation.

Recent evidence points to a baroreceptor mediated influence on post exercise thermal responses (Kenny, Jackson, and Reardon, 2000), subsequent to the post exercise hypotensive effect of persistent peripheral tissue vasodilation, that has been observed following acute bouts of exercise (Kaufman et al., 1987; Wilcox et al., 1982). Manipulating post exercise venous pooling, by means of head down tilt (Kenny, Jackson, and Reardon, 2000) and application of lower body positive pressure (Jackson et al., 2000), in an effort to reverse its impact on baroreceptor unloading was shown to result in a relative lowering of the resting post-exercise elevation in the threshold for cutaneous vasodilation.

It has been suggested that the resultant post exercise peripheral vasodilation may cause a pooling of the warmed blood thus entrapping the residual heat of muscle (Piepoli et al., 1993). This would result in a decrease of local convection thereby slowing the residual heat loss of muscle. The net effect would be a temporary increase in the post-exercise muscle tissue heat content. Thus in conjunction with a post-exercise decrease in heat loss response for both SkBF and sweating (Kenny, Proulx, Denis, and Giesbrecht, 2000) and an elevated muscle heat load, there would be a time-dependent transfer of the residual heat of muscle to the core during the post-exercise resting period. These data supports the need to further investigate the mechanism(s) of local tissue heat balance following different conditions of exercise in order to forward our understand of non-thermoregulatory influences, such as baroreceptor control, on post-exercise temperature regulation.

Thus the following study was designed to study the dynamics of core, muscle and skin temperature changes during and following isolated muscle work. Specifically, the role of non-active tissue in the retention and dissipation of heat during and following intense isolated knee extensions.

**Methods**

**SUBJECTS**

Subsequent to approval of the project by the University Human Research Ethics Committee, 6 healthy subjects (5 males, 1 female) with no history of cardiovascular or respiratory disease, consented to participate in the study. Subjects were physically active, although none engaged in daily or intensive training programs. Mean values (± SE) of the subject’s age, height, body mass, $V_{\text{O}}_{2\text{max}}$ during single knee extensions and body fat content were 23 ± 4 years, 1.7 ± 0.4 m, 81.9 ± 6.4 kg, 1.9 ± 0.7 l · min⁻¹ and 11.8 ± 1.9%. The female subject was eumenorrheic with regular, approximately 28-day long menstrual cycles. To control for hormonal effects the female subject was studied within 9 days after start of menstruation (follicular phase).
INSTRUMENTATION

Esophageal temperature was measured using a thermocouple temperature probe (Mallinckrodt Medical, Mon-a-therm®, St-Louis, USA) inserted through a nostril, into the esophagus to the level of the heart (Mekjavic and Rempel, 1990). Muscle temperature of the non-exercising leg was measured using a flexible thermocouple temperature probe (Physitemp Instruments Inc, Clifton, NJ, USA, Model IT-17:3 Type T stranded thermocouple wire) inserted into the deep vastus medialis by use of a method described elsewhere (Kenny et al., 2002). Ultra-sound imaging was used to discern the best perpendicular insertion tract and subsequently to place the probe at a position 10 mm and equidistant from the deep femoral artery and the femur. The implant site was approximately midway between and medial to a line joining the anterior superior iliac spine and the superior aspect of the center of the patella. Each probe had 3 thermocouples, one positioned at the tip, one at 15 and the third at 30 mm from the tip. In placing the probe in a plane perpendicular to the long axis of the thigh, and by placing a surface thermocouple near the site of insertion, the linear four-point temperature gradient was measured between deep muscle (10 mm from the deep femoral artery and the femur) and the skin surface. The probe assembly was secured to the skin with sterile, waterproof transparent dressing and tape. After the experiment and upon removal, the probes were inspected for any kinks or folds and were measured for length. In no case was the probe displaced nor was it deformed. Thus, while no post-exercise ultrasound verification was made, it was concluded that the probe position was unaltered by the exercise protocol.

Whole-body mean skin temperature ($T_{sk}$) and heat flux ($HF_{sk}$) were measured using waterproofed temperature and heat flow sensor with integral linear thermistor (Concept Engineering, Old Saybrook, CT, model FR-025-TH44018-6) placed at 11 surface sites. The area-weighted mean was calculated by assigning the following regional percentages: head 6%, upper arm 9%, forearm 6%, finger 2%, chest 19%, upper back 9.5%, lower back 9.5%, anterior thigh 10%, posterior thigh 10%, anterior calf 9.5%, posterior calf 9.5% (Layton et al., 1983).

Sweat rate was measured using a ventilated capsule having an area of 5.0 cm$^2$ placed on the upper back. Anhydrous compressed air was passed through the capsule over the skin surface at a rate of $1 \text{ l} \cdot \text{min}^{-1}$. Vapor density of the effluent air was calculated from the relative humidity and temperature of the air measured by an Omega HX93 humidity and temperature sensor (Omega Engineering, Stanford, CT, USA) at a known barometric pressure. Sweat rate was the product of the difference in water content between effluent and influent air, and the flow rate. This value was adjusted for the skin surface area under the capsule and expressed in mg · min$^{-1}$ · cm$^{-2}$.

Forearm skin blood flow (SkBF) was assessed by laser-Doppler flowmetry with a probe placed on the right mid-anterior forearm (TSI, St. Paul, Minn., USA, Model BPM 403A Blood Perfusion Monitor). The laterally reading laser-Doppler sensor (TSI, St. Paul, Minn., USA, Right Angle Probe P-430) was taped to the cleaned skin surface at a location that gave a consistent reading. Only relative values were used and no attempt was made to evaluate absolute blood flow.

Oxygen consumption ($V\text{O}_2$) was determined by open circuit analysis using an automated gas collection system (Quinton Instrument Co, Seattle, Washington,
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USA, Model Q-Plex 1 Cardio-Pulmonary Exercise System). Heart rate (HR) was recorded by means of wireless transmission (Polar Electro, Sport Tester PE3000). Temperature and heat flux data were collected and digitized (Hewlett Packard data acquisition module, model 3497A) at 5-s intervals, simultaneously displayed and recorded in spreadsheet format on a hard disk (Hewlett Packard, model PC-312, 9000).

EXPERIMENTAL PROTOCOL

Subjects performed an incremental isotonic test (constant angular velocity, increases in force output) on the KIN-COM™ isokinetic apparatus (Chattech Corporation, Hixson, Tennessee, USA, Model KIN-COM™ 500H Muscle testing and training system) to determine their maximal capacity (V·O₂ max). The exercise consisted of unilateral, concentric knee extension over a range of 70° from perpendicular with the subject sitting (hip angle between 90° and 110°) and the long axis of the thigh in the horizontal plane. The subject was firmly restrained in a fashion so as to immobilize the thigh of the active leg, the hips and the upper body. The load was placed above the foot on the ventral surface at the level of the distal end of the tibia in order to minimize the contraction of the muscles of the lower leg. The arms and the inactive leg were left unrestrained in order to ensure minimal contribution to the force development by these segments. The resistance was increased by 15 newtons every two minutes until fatigue while the angular velocity was maintained at 58.3°sec⁻¹ throughout the test. The results of the test were used to establish the work level for the experimental trial.

The experimental trial was conducted in the morning following a 24 h period without heavy or prolonged physical activity, the last 12 h of which included abstinence from stimulants and alcohol, 8 h of sleep and a minimum of 0.25 l of water during each waking hour. On each study day, care was taken to avoid major thermal stimuli or substantial increase of metabolic rate between awakening and the start of the experiment.

Following the insertion of the intra-muscular probe, subjects rested in a semi-recumbent position for 60 min at an ambient temperature (Tₐₚₚ) of 22 °C. During this period, the subject was instrumented appropriately and then remained resting, seated for a period of 30 min. Subjects then performed 15 min of exercise as above consisting of unilateral, concentric knee extension over a range of 70° from perpendicular against a dynamic resistance sufficient to elicit a heat load of 3.5 kJ kg⁻¹. This was calculated for each subject from the pre-test data using the oxygen consumption, the respiratory exchange ratio and the average measured mechanical efficiency of this movement. On the average, this worked out to be approximately 60% V·O₂ max. Exercise was followed by 60 min of seated rest.

The total energy (Eₜₒₜ) expended as a result of exercise, during the period from onset of exercise until the time at which oxygen consumption returned to pre-exercise values, was calculated from the sum of the energy expended (E) using the following equation (expressed in kilojoules):

$$ E_{\text{tot}} = \sum E_{\text{e/r}} = \sum \left( \dot{V} O_2 \cdot \left[ \frac{\text{carbohydrate}}{0.3} \cdot \epsilon_c + \left( \frac{\text{fat}}{0.3} \cdot \epsilon_f \right) \right] \right) $$

where $E_{\text{e/r}}$ = rate of energy expenditure during exercise and recovery, $\epsilon_c$ = the caloric equivalent in kilojoules per litre of oxygen for carbohydrates, $\epsilon_f$ = the caloric
equivalent in kilojoules per litre of oxygen for fat, and \( \text{RER} \) = the respiratory exchange ratio. The minute values were summed for the entire period as described above.

The mechanical (W) done during each contraction of the exercise phase was measured and recorded using the KIN-COM Isokinetic machine. This was calculated from the force exerted and the angular displacement during the knee extension:

\[
W = T \theta
\]

where \( T \) is rotational force or torque and \( \theta \) is the angular displacement.

The total work done (\( W_{\text{TOT}} \)) was the sum of the work accomplished during each of the contractions during the 15 minutes of exercise.

Mechanical efficiency (\( E_M \)) was defined as the total work completed during the 15 minute exercise period divided by the total energy expended minus the resting metabolic rate (\( E_{\text{TOT}} - \text{RMR} \)). Thus:

\[
E_M = \frac{W_{\text{TOT}}}{E_{\text{TOT}} - \text{RMR}}
\]

The resting metabolic rate (RMR) was calculated from the average rate of oxygen consumption during the five minutes preceding the exercise bout. These values were calculated and expressed in kilojoules using the aforementioned equation. The total heat load (H) generated by the exercise for each subject was calculated by subtracting the average rate of heat production at rest (\( H_{\text{RMR}} \)) and the energy equivalent of the total mechanical work done (\( W_{\text{TOT}} \)) from the total energy expenditure (\( E_{\text{TOT}} \)). Values are expressed in kilojoules:

\[
H = E_{\text{TOT}} - (H_{\text{RMR}} + W_{\text{TOT}})
\]

The dry heat loss (HL), or that heat lost by radiation and conduction from the skin surface, during exercise and during recovery was estimated by subtracting the area weighted mean heat flux (\( H_{sk} \)) (as above) corrected for body surface area (BSA) during rest from those values recorded during exercise and recovery respectively. Thus:

\[
HL_{\text{ex}} = (H_{sk} \cdot \text{BSA})_{\text{ex}} - (H_{sk} \cdot \text{BSA})_{\text{rest}}
\]

and

\[
HL_{\text{rec}} = (H_{sk} \cdot \text{BSA})_{\text{rec}} - (H_{sk} \cdot \text{BSA})_{\text{rest}}
\]

The dry heat loss during exercise (\( HL_{\text{ex}} \)) and during recovery (\( HL_{\text{rec}} \)) was the total dry heat lost during the 15 minute exercise and 60 minute recovery periods respectively.

ANALYSIS OF RESULTS

Statistical analyses, for \( T_c, T_a, T_{mu} \), heat flux, and HR was performed by ANOVA for repeated measures to compare values for baseline (average of final 5 min),
end-exercise, and at 10 min intervals post-exercise. Data are presented as means ± SE.

Results

In setting the workload resistance as a function of the relative heat load and mechanical efficiency for each subject there was some variability in the recorded maximum and minimum values for total energy expenditure, mechanical work and heat load (Table 1). The averages for these parameters respectively were 455.5 ± 39.8 kJ, 24.6 ± 4.3 kJ and 292.3 ± 33.7 kJ. The average total dry heat loss during the exercise bout was 7.0 ± 1.6 kJ and during the 60 minutes of recovery the average heat loss was −12.3 ± 6.1 kJ.

HEAT LOAD AND HEAT LOSS RESPONSE

The time-course changes in heat load (H) and dry heat loss from the skin (HL) are represented in Figure 1. At rest the dry heat loss (HL) defined relative to heat load, that is minus the resting values, was essentially zero and increased to a maximal level of 1.3 kJ per minute between 13 and 15 minutes of exercise. This heat loss returned to zero within 5 minutes of recovery. The heat production on the other hand showed a gradual and linear increase of about 0.93 kJ · min$^{-1}$ between 2 and 15 minutes of exercise. At cessation of exercise the heat production dropped precipitously to attain a stable value at four minutes of recovery that was slightly higher than, but not significantly different from pre-exercise values. Both SkBF and sweat rate increased slightly above baseline resting during the first 5 minutes of exercise. After 10 minutes of exercise, SkBF and sweat rate increased in a linear fashion until cessation of exercise. SkBF and sweat rate decreased quickly following exercise to reach resting values within ~2 and 7 minutes of exercise recovery respectively (Figure 2).

Table 1  Mean and Individual Mechanical Energy, Heat Load and Heat Loss Data

<table>
<thead>
<tr>
<th>Subject</th>
<th>Resistance (N)</th>
<th>ME (%)</th>
<th>$E_{TOT}$ (kJ)</th>
<th>Work (kJ)</th>
<th>H (kJ)</th>
<th>$HL_{ex}$ (kJ)</th>
<th>$HL_{rec}$ (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70</td>
<td>5.99</td>
<td>539.6</td>
<td>24.9</td>
<td>390.5</td>
<td>12.0</td>
<td>−5.7</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>4.47</td>
<td>471.4</td>
<td>14.2</td>
<td>303.7</td>
<td>1.9</td>
<td>−3.4</td>
</tr>
<tr>
<td>3</td>
<td>85</td>
<td>12.29</td>
<td>526.8</td>
<td>42.6</td>
<td>303.9</td>
<td>7.1</td>
<td>−22.7</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>5.99</td>
<td>455.5</td>
<td>19.3</td>
<td>303.4</td>
<td>9.4</td>
<td>−21.6</td>
</tr>
<tr>
<td>5</td>
<td>45</td>
<td>7.59</td>
<td>449.6</td>
<td>24.3</td>
<td>295.4</td>
<td>6.5</td>
<td>−27.5</td>
</tr>
<tr>
<td>6</td>
<td>35</td>
<td>12.46</td>
<td>290.4</td>
<td>22.4</td>
<td>157.1</td>
<td>5.1</td>
<td>7.3</td>
</tr>
<tr>
<td>Mean</td>
<td>54.2</td>
<td>8.13</td>
<td>455.5</td>
<td>24.6</td>
<td>292.3</td>
<td>7.0</td>
<td>−12.3</td>
</tr>
<tr>
<td>SEM</td>
<td>8.2</td>
<td>1.54</td>
<td>39.8</td>
<td>4.3</td>
<td>33.7</td>
<td>1.6</td>
<td>6.1</td>
</tr>
</tbody>
</table>
EXERCISE TEMPERATURE RESPONSE

Baseline $T_e$ and $T_{sk}$ were 37.01 ± 0.11 °C and 31.81 ± 0.32 °C, respectively. Muscle tissue temperature was significantly lower than $T_e$ by ~0.45 °C with the difference between greater from the deeper to outer section of the muscle (i.e., 0.42, 0.45 and 0.55 °C for $T_{mu10}$, $T_{mu25}$, and $T_{mu40}$, respectively) ($p < .05$) (Table 2). The rate of tissue heat production during the 15 min single leg knee extensions was sufficient to result in a significant elevation of core temperature of 0.31 °C ($p < .05$) and an increase in the contra-lateral resting muscle temperature of 0.23, 0.19 and 0.09 °C for $T_{mu10}$, $T_{mu25}$ and $T_{mu40}$, respectively ($p < .05$). $T_{sk}$ increased to an elevated value 0.37 °C above baseline value (n.s.). The increase in $T_{sk}$ was paralleled by an increase in the rate of heat loss (Figure 2).

In contrast to baseline resting, the measured temperature gradient between the core (i.e., $T_e$) and muscle ($T_{mu}$) increased with exercise (i.e., 0.48, 0.55 and 0.75 °C for $T_{mu10}$, $T_{mu25}$, and $T_{mu40}$, respectively) with the largest difference measured for the outer muscle section (i.e., $T_{mu40}$) ($p < .05$) (Figure 3). As demonstrated in Figure 3, the temperature gradient of the resting muscle increased more quickly in the deep ($T_{mu10}$) region of the muscle as compared to the superficial ($T_{mu40}$) region. As a result the measured temperature gradient between $T_{mu10}$ and $T_{mu40}$ increased from 0.13 °C at rest to 0.27 °C end exercise ($p < .05$).

POST-EXERCISE TEMPERATURE RESPONSE

Esophageal temperature remained significantly elevated at end exercise values for the ~2 min after which $T_{es}$ showed a rapid decrease (0.13 °C) followed by a more gradual decrease to baseline values within 15 min. In contrast, muscle temperature

![Figure 1.](https://example.com/figure1.png)
Figure 2. Mean (SD) esophageal (□) and resting contra-lateral muscle (T_{m10}, ○; T_{m25}, △; and T_{m80}, ▽) temperatures (top), mean skin temperature (⊗), thigh heat flux (▲) and whole body heat flux (●) (middle) and sweat rate (x) and relative forearm skin blood flow (+ bottom) during baseline resting, exercise and post-exercise resting (n = 6).
Table 2  Mean Body Core, Contra-Lateral Resting Muscle and Thigh Skin Temperatures and Temperature Gradients

<table>
<thead>
<tr>
<th></th>
<th>Baseline resting</th>
<th>End exercise</th>
<th>Post-exercise recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>5 min</td>
</tr>
<tr>
<td>$T_{es}$</td>
<td>37.00</td>
<td>37.31*</td>
<td>37.25*</td>
</tr>
<tr>
<td>$T_{mus0}$</td>
<td>36.58</td>
<td>36.81*</td>
<td>36.83*</td>
</tr>
<tr>
<td>$T_{mus25}$</td>
<td>36.55</td>
<td>36.74*</td>
<td>36.79*</td>
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<tr>
<td>$T_{mus40}$</td>
<td>36.45</td>
<td>36.54</td>
<td>36.59*</td>
</tr>
<tr>
<td>$T_{thigh}$</td>
<td>31.43</td>
<td>32.15</td>
<td>32.09</td>
</tr>
<tr>
<td>$T_{es} - T_{mus0}$</td>
<td>0.42</td>
<td>0.48</td>
<td>0.42</td>
</tr>
<tr>
<td>$T_{es} - T_{mus25}$</td>
<td>0.45</td>
<td>0.55</td>
<td>0.46</td>
</tr>
<tr>
<td>$T_{es} - T_{mus40}$</td>
<td>0.55</td>
<td>0.75*</td>
<td>0.66</td>
</tr>
<tr>
<td>$T_{mus0} - T_{mus25}$</td>
<td>0.03</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>$T_{mus0} - T_{mus40}$</td>
<td>0.13</td>
<td>0.27*</td>
<td>0.24</td>
</tr>
<tr>
<td>$T_{mus25} - T_{mus40}$</td>
<td>0.10</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>$T_{mus0} - T_{thigh}$</td>
<td>5.15</td>
<td>4.66</td>
<td>4.74</td>
</tr>
<tr>
<td>$T_{mus25} - T_{thigh}$</td>
<td>5.12</td>
<td>4.59</td>
<td>4.70</td>
</tr>
<tr>
<td>$T_{mus40} - T_{thigh}$</td>
<td>5.02</td>
<td>4.39</td>
<td>4.50</td>
</tr>
</tbody>
</table>

* indicates significant difference from baseline resting ($p < .05$).
continued to rise slightly reaching peak values ~10 min post-exercise (i.e., 0.25, 0.26 and 0.15 °C above baseline resting for \( T_{mu10} \), \( T_{mu25} \), and \( T_{mu40} \), respectively) \((p < .05)\). This was followed by a slow gradual decrease in temperature during the course of the 60 min recovery period to values 0.10, 0.09 and 0.16 °C below baseline resting for \( T_{mu10} \), \( T_{mu25} \), and \( T_{mu40} \), respectively. Following the initial 10 min of recovery (after \( T_{es} \) reached peak values), the temperature gradient between \( T_{es} \) and \( T_{mu} \) increased demonstrating the gradual cooling of muscle that contrasted the stable \( T_{es} \) measured for the duration of recovery. Thus, while \( T_{es} \) decreased to baseline values within ~15 min of end exercise, \( T_{mu} \) reached pre-exercise resting values following ~40 min of recovery.

With respect to the temperature gradient across the resting muscle, it was noted that the muscle temperature profile was similar during the post-exercise period. The temperature gradient between \( T_{mu10} \) and \( T_{mu25} \) was minimal (i.e., ~0.03 °C). The largest temperature gradient measured between consecutive measured points in muscle was between \( T_{mu25} \) and \( T_{mu40} \) (~0.20 °C) \((p < .05)\). \( T_{es} \) decreased slowly to reach a stable value at 30 minutes of ~32.0 °C that was maintained for the duration of the post-exercise recovery (n.s.).

HEART RATE RESPONSE

Heart rate increased abruptly from a baseline resting value of 69 beats · min\(^{-1}\) to an elevated value of 103 within 5 minutes of exercise onset. Heart rate showed a gradual increase over the duration of exercise to 118 and 132 beats · min\(^{-1}\) at 10 and 15 min exercise respectively. Post-exercise initial heart rate recovery to about 98 beats · min\(^{-1}\) or less than 50% of the exercise response occurred within 10 min and the remaining recovery was slower decreasing to baseline resting values at ~25 min (73 beats · min\(^{-1}\)).
Discussion

The purpose of this study was to develop a better understanding of the relative changes in temperature of different body compartments during exercise and post exercise recuperation. Specifically the aim was to study the role of non-active tissue in the retention and dissipation of heat during and following intense isolated knee extensions. The contraction of the quadriceps muscle group during unilateral knee extension against a constant dynamic resistance at constant velocity was an ideal means of developing an internal heat load. This movement has a relatively low mechanical efficiency of $8.13 \pm 1.54\%$ and therefore serves well to impose a high heat load ($292.32 \pm 0.46 \text{ kJ}$) at low work output ($24.61 \text{ kJ} \pm 4.31$). Thus, this workload was sufficient to induce a significant elevation of body core ($0.31 ^\circ\text{C}$) and inactive muscle tissue ($0.23 ^\circ\text{C}$ for deep muscle) temperature and the subsequent activation of the warm thermal responses. Further, in isolating the muscle contractions, the contribution of collateral muscle activity to the heat load is minimized. The average rate of energy expended during the exercise phase increased gradually over the 15-minute period and declined rapidly during the recovery phase. As a result, the heat load ($H$) shown in Figure 1 increased continuously from $17 \text{ kJ} \cdot \text{min}^{-1}$ at the onset of exercise to $33.72 \text{ kJ} \cdot \text{min}^{-1}$ after 15 minutes of exercise and decreased to resting levels within 7 to 10 minutes of recovery.

Of the average total $292.3 \text{ kJ}$ heat load produced by exercise, a certain amount was either lost by conduction (dry heat loss) or evaporation and the balance was stored in other tissue. This occurred during the exercise bout itself and during the post-exercise rest period. During exercise a relatively small amount of heat, on the average 7 kJ, was lost through dry heat loss. During the 60 minute post-exercise rest period there was a net heat absorption by conduction of an average 12.3 kJ. At the maximal rate of heat production of $33.72 \text{ kJ} \cdot \text{min}^{-1}$, after 13 to 15 minutes of exercise, the rate of dry heat loss was only $1.31 \text{ kJ} \cdot \text{min}^{-1}$. Although the heat loss by evaporation was not measured, there was heat loss by evaporation during and after the exercise bout. It is clear in Figure 2 that the sweat rate increased significantly from resting levels of less than $0.1 \text{ mg} \cdot \text{min}^{-1} \cdot \text{cm}^{-2}$ only after 5 minutes of exercise to $0.3 \text{ mg} \cdot \text{min}^{-1} \cdot \text{cm}^{-2}$ at 8 minutes of exercise. The sweat rate reached a peak of $0.65 \text{ mg} \cdot \text{min}^{-1} \cdot \text{cm}^{-2}$ only after 15 minutes of exercise. Subsequently, it decreased to minimal values within 10 minutes post exercise. Inasmuch as the sweat rate may indicate evaporative heat loss and, based on the changes in esophageal and muscle temperatures, it is concluded that a large portion of the remaining heat load was absorbed by other tissues.

As indicated above, exercise resulted in a significant elevation of esophageal temperature of $0.31 ^\circ\text{C}$ above baseline resting and a subsequent increase in the contra-lateral resting muscle temperature (i.e., $0.23, 0.19$ and $0.09 ^\circ\text{C}$ for the deep, mid and outer muscle regions respectively). The increase of the inactive thigh muscle temperature subsequent to the increase in active muscle and esophageal temperature indicates the importance of the role that vascular heat transfer plays in the cooling of active tissue and the distribution of heat to other tissues of the body. As such it is essential to reducing the rate of body core temperature increase during exercise. Previous studies have reported slight decreases or no changes of inactive muscle temperature during dynamic exercise (Aikas et al., 1962; Asmussen and Boje, 1945; Buchthal et al., 1945) despite a significant increase
in both body core temperature and muscle temperature of the exercising legs. The lack of temperature increase in the inactive muscle tissue during exercise was said to indicate a proportional decrease in tissue perfusion and therefore remained unchanged or was reduced from resting values. Studies specifically examining forearm blood flow during leg exercise have demonstrated significant cutaneous vasodilation and simultaneous vasoconstriction in inactive muscle tissue with rising core temperatures (Bevegard et al., 1966; Blair et al., 1961; Kamon et al., 1969).

It is noteworthy that estimates of temperature change in inactive muscle tissue in previous studies were performed in muscle tissue of the upper limbs. It is possible that regional differences in both hemodynamics and the muscle mass to blood perfusion ratio may significantly affect the dynamics of heat distribution to inactive muscle tissue during exercise and subsequent recovery (Rowell, 1974). With respect to regional hemodynamics Nishiyasu et al. (1992) demonstrated that during 30 min of one leg exercise, SkBF response to an increase in body core temperature in inactive regions such as calf and forearm were markedly different. It was shown that under such conditions SkBF response is reduced in the lower extremities as compared to the upper limbs. This increase in SkBF in the upper limbs results in an increase of heat loss from the surface and subsequent cooling of venous blood. The resultant gradient created by the cooler venous blood significantly increases conductive heat loss and thereby reduces the rate of increase of inactive muscle temperature. This is analogous to what occurs in active musculature (Gisolfi and Robinson, 1970).

The difference in the ratio of muscle mass to blood perfusion between upper and lower limbs may explain the differential increase in temperature of the lower limb (Nishiyasu et al., 1992). That is, the increased ratio of the lower limb would tend to decrease the temperature gradient across the muscle and thereby decrease the conductive heat loss. It is noteworthy that we did observe a non-significant, transient increase in both thigh skin temperature and heat loss during mid-exercise. Both decreased to resting values before peak inactive muscle temperature was reached. This demonstrates that conductive heat loss of the thigh was indeed limited.

Aulick et al. (1981) demonstrated that inactive muscle tissue likely plays a significant role in heat transfer from body core using measures of intravascular temperature at the level of the axilla. They showed that, light dynamic exercise (~30% of VO2max) resulted in an end exercise arterial-venous temperature difference of ~2.9 °C. End exercise blood temperatures in the axillary artery and vein were ~37.1 and 34.2 °C compared to resting values of 36.7 and 35.3 °C, respectively. If we consider that our measurement technique placed us within close proximity of the femoral artery and vein of the inactive muscle, we can speculate that the changes measured by Aulick et al. (1981) are comparable to those measured in deep muscle in the inactive thigh (i.e., located 10 mm from the deep femoral artery and vein). It is therefore plausible that the net increase in deep muscle temperature during exercise is to some extent attenuated by the increasing arterial-venous temperature difference (i.e., countercurrent exchange).

Of interest as well was the observation that muscle temperature of the resting leg continued to rise gradually during recovery to reach peak values at ~10 min post exercise. During the same period a decrease in esophageal temperature (i.e., 0.19 °C) and the rate of heat loss was registered. Those studies that demonstrated
no change or only a slight decrease in the inactive muscle temperature during exercise did demonstrate an end-exercise increase and subsequent sustained elevation of resting inactive muscle temperature. The increase in inactive muscle temperature occurred while both active muscle and esophageal temperatures decreased quickly during the initial minutes of recovery (although temperatures remained higher than inactive muscle temperature) (Aikas et al., 1962). Although a mechanism for the post-exercise rise or sustained elevation in muscle temperature of the inactive leg was not presented, based on our observations, it is likely that inactive tissue continues to act as a heat sink for the central circulation. As indicated in Table 2, a significant gradient remains between body core and deep muscle (i.e., Δ0.42 °C) which was comparable to that measured at end exercise. Since inactive muscle tissue temperature remained significantly cooler than either body core (and most likely previously active muscle), vascular transfer of heat to these regions would be maintained or increased in the face of a measurable decrease in whole-body heat loss, SKBF and sweating response (Figure 2).

The temperature gradient measured across the vastus medialis provides an interesting overview of tissue temperature dynamics. As demonstrated in Figure 3, thigh temperature across the radial distance of the thigh varied slightly between resting, end exercise and post-exercise resting conditions. The smallest temperature gradient measured between deep and superficial muscle occurred during baseline resting (i.e., \( T_{\text{mu10}} - T_{\text{mu40}} \) equal to 0.10 °C). A negligible difference was measured between deep and mid muscle temperature (i.e., \( T_{\text{mu10}} - T_{\text{mu25}} \) equal to 0.03 °C). The gradient between deep and superficial muscle increased significantly at end exercise to 0.27 °C with only a slight increase in the deep to mid muscle temperature gradient. During the post-exercise period the muscle tissue temperature profile remained unchanged. Although the temperature gradient between deep and superficial muscle decreased slightly from end exercise it remained elevated above baseline resting. Again only a negligible difference was measured between deep and mid muscle. As noted in Figure 3, the magnitude of the post-exercise temperature response decreased progressively, without a change in the temperature profile, to values below baseline resting at the end of the 60 min recovery. Although previous studies have demonstrated a decrease in inactive tissue below resting values (Aikas et al., 1962), the mechanism for this response is unclear. Interestingly our observation was that thigh skin temperature of the inactive limb paralleled the progressive decrease in the inactive thigh muscle tissue temperature. This response would favor an increase in conductive heat loss of the residual heat of muscle to the skin surface.

In conclusion, these data demonstrate that the rate of tissue heat production of the active muscle was sufficient to result in a significant elevation of esophageal temperature and a subsequent increase in contra-lateral inactive leg muscle temperature. Although heat loss from the inactive leg increased above resting during mid-exercise, it actually decreased to resting values before peak muscle temperature was reached (i.e., at ~10 min of post exercise recovery). Our results support the concept of the importance of convective heat transfer by blood to inactive muscle tissue in reducing the rate of core temperature increase during exercise. In addition, the sustained increase in inactive muscle temperature during the early stages of recovery, in contrast to the decrease of esophageal temperature and rate of heat loss, demonstrates the potential role of inactive muscle tissue as a heat sink.
during recovery. Although the transfer of heat to the cooler tissue regions may act as a heat sink during exercise, thereby reducing the thermal stress, it results in a significant residual heat load during subsequent recovery. This may in fact increase recovery time to re-establish normal resting temperatures.

References


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