Real-time Assessment of Thermal-Work Strain: Algorithmic Basis and Validity

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The views expressed in this presentation are those of the author and do not reflect the official policy of the Department of Army, Department of Defense, or the U.S. Government.
• Thermal-Work Strain Monitoring Need
• Solution: The Physiological Strain Index (PSI)
• Problem of measuring Core Temp.
• Estimated Core Temperature (ECTemp) Model
  – Physiological Basis of Model
  – Development
  – Validation
• Real-time use of ECTemp in PSI
Thermal-Work Strain State?
Engine Strain
Thermal Work Strain

HR + CT
Physiological Strain Index (PSI)

\[ PSI = 5 \left( \frac{CT_t - CT_{rest}}{39.5 - CT_{rest}} \right) + 5 \left( \frac{HR_t - HR_{rest}}{180 - HR_{rest}} \right) \]

- Simple 0 to 10 index
- PSI = 10
  - HR = 180 beats/min.
  - CT = 39.5 °C (103.1 °F)
  - Thermal injury is likely

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*Moran DS, Shitzer A, and Pandolf KB 1998, Moran DS 2000*
Problem of CT Measurement

• Rectal /Esophageal
  – Lab gold standards
  – Not practical in field

• Core temperature pill
  – Works in controlled studies
  – Costly, contra-indicated for some,
  – Prone to error with ingested fluids

• Skin and Tympanic Temperatures
  – Error from environment, error from placement,
    individual differences
Estimated Core Temp. Model
Estimated Core Temp. Model
Estimated Core Temp. Model

HR “Noisy” Observation of Core Temp

Estimation of human core temperature from sequential heart rate observations


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2 Defense Science and Technology Organization, Melbourne, Australia
3 Marine Corps Systems Command, Quantico, VA 22135, USA
4 Department of Computer Science, Brown University, Providence, RI 02912, USA

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UNCLASSIFIED
1. To use a Kalman Filter you need two models:
   i. How does core body temperature change from time step to time step?
   ii. How does steady state core temperature relate to steady state heart rate?
Algorithm Validation

- 9 Studies, 87 Subjects, >50,000 data points
- Different: Exercise Intensity, Environmental Conditions, Clothing (shorts and t-shirt – full encapsulation), Hydration, and Acclimation.

<table>
<thead>
<tr>
<th>Study</th>
<th>Time (min.)</th>
<th>n</th>
<th>Age (yrs)</th>
<th>Height (m)</th>
<th>Wt. (kg)</th>
<th>Body Fat (%)</th>
<th>TEE Rate (W)†</th>
<th>Air Temp. (°C)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>~480 x 6</td>
<td>18*</td>
<td>22±4</td>
<td>1.77±0.04</td>
<td>81±15</td>
<td>N/C</td>
<td>350/470</td>
<td>20–40</td>
<td>30–50</td>
</tr>
<tr>
<td>B</td>
<td>121/121</td>
<td>8</td>
<td>23±3</td>
<td>N/C</td>
<td>72±12</td>
<td>N/C</td>
<td>1000</td>
<td>33</td>
<td>50</td>
</tr>
<tr>
<td>C</td>
<td>111/28</td>
<td>6/8</td>
<td>23±6</td>
<td>1.76±0.06</td>
<td>76±15</td>
<td>18±6</td>
<td>675</td>
<td>35</td>
<td>55</td>
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<tr>
<td>D</td>
<td>59/100</td>
<td>7</td>
<td>24±7</td>
<td>1.78±0.08</td>
<td>80±21</td>
<td>16±11</td>
<td>550</td>
<td>45</td>
<td>20</td>
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<tr>
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<td>209+250</td>
<td>8</td>
<td>21±1</td>
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The algorithm has been validated across a large population including:

- U.S. Marines in Iraq and Afghanistan
- U.S. Army Ranger Students
- U.S. Special Forces
Results

Estimation Algorithm
Bias = $-0.03^\circ$C
95% of estimates fall within $\pm 0.63^\circ$C

Gold Standard
Bias = $0.06^\circ$C
95% within $\pm 0.58^\circ$C
Results

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The algorithm is on par with laboratory gold standard probe methods (e.g. rectal and esophageal probes)
CBRNE Validation

- 22\textsuperscript{nd} Chemical Battalion, 1\textsuperscript{st} WMD-CST, 95\textsuperscript{th} WMD-CST
- 3 Different CBRNE Training Events
  - 45 to 90 minute events over 2 to 3 days
Analysis

• Performance
  – Root Mean Square Error (RMSE)
  – Bias and Limits of Agreement (LoA)

• Questions
  – Does the model perform the same between:
    • Training events
    • Volunteers who got the hottest versus those who remained cool
    • Different time points
Event and Hot/Cool Differences?

Hot = Quartile of “hottest” (highest core temperatures)
Cool = Quartile of “coolest” (lowest core temperatures)

• No significant differences between:
  • Event
  • Hottest quartile and Coolest quartile
Overall Results

Bias = 0.02°C, LoA = ± 0.48°C
Overall Results

Bias = 0.02°C, LoA = ± 0.48°C

The algorithm appears to perform better when wearing chem/bio protection.
Thermal-Work Strain State

Physiological Strain Index (PSI)

Simple 0 to 10 index

PSI = 10

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Practical Application

Bias = 0.05, LoA = ± 1.00

Δ TWSI (Est. - Obs.)

Mean TWSI (Obs. and Est.)

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• Small bias and limits of agreement - 0.01 ± 1.20

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Very good agreement with observed PSI
Small variance across individuals

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Real-Time Use


- 22nd Chemical Battalion, 1st WMD-CST, 95th WMD-CST, (2012 and 2013)
Real-Time Use


High PSI used to identify Marine who was struggling

PSI predicted 15 minutes into the future
Conclusions

• Core temperature prediction algorithm:
  – based on classic physiology and established signal processing methods
  – performance similar to laboratory gold standard
• Validated and independently verified
• Using estimated core temperature within PSI has been demonstrated in real-time during field training
Example Heat Casualty

Field: Heat Casualty, 32 C 45% RH
RMSD = 0.18 C (N=1)
Example Heat Casualty

In this case the algorithm’s estimate of core body temperature is almost on top of the measured core body temperature. Especially during the rapid rise to 39.5 °C!