Original Article
The relationship between skeletal muscle mitochondrial citrate synthase activity and whole body oxygen uptake adaptations in response to exercise training

Andreas Vigelsø*, Nynne B Andersen*, Flemming Dela

Xlab, Center for Healthy Aging, Department of Biomedical Sciences, Faculty of Health Sciences, University of Copenhagen, Denmark. * Equal contributors.

Received April 3, 2014; Accepted May 12, 2014; Epub July 12, 2014; Published July 15, 2014

Abstract: Citrate synthase (CS) activity is a validated biomarker for mitochondrial density in skeletal muscle. CS activity is also used as a biochemical marker of the skeletal muscle oxidative adaptation to a training intervention, and a relationship between changes in whole body aerobic capacity and changes in CS activity is often assumed. However, this relationship and absolute values of CS and maximal oxygen uptake ($\dot{V}O_{2max}$) has never been assessed across different studies. A systematic PubMed search on literature published from 1983 to 2013 was performed. The search profile included: citrate, synthase, human, skeletal, muscle, training, not electrical stimulation, not in-vitro, not rats. Studies that reported changes in CS activity and $\dot{V}O_{2max}$ were included. Different training types and subject populations were analyzed independently to assess correlation between relative changes in $\dot{V}O_{2max}$ and CS activity. 70 publications with 97 intervention groups were included. There was a positive ($r = 0.45$) correlation ($P < 0.001$) between the relative change in $\dot{V}O_{2max}$ and the relative change in CS activity. All reported absolute values of CS and $\dot{V}O_{2max}$ did not correlate ($r = -0.07$, $n = 148$, $P = 0.4$). Training induced changes in whole body oxidative capacity is matched by changes in muscle CS activity in a nearly 1:1 relationship. Absolute values of CS across different studies cannot be compared unless a standardized analytical method is used by all laboratories.

Keywords: Citrate synthase, endurance training, high-intensity interval training, human skeletal muscle, maximal oxygen uptake

Introduction
Cardiac output and not skeletal muscle enzymatic activity is the limiting factor to aerobic performance in healthy people [1]. Nevertheless, adequate muscle enzymatic activity in e.g. glycolysis and Krebs cycle is necessary for a high performance and maximal oxygen uptake ($\dot{V}O_{2max}$). Enzymatic activity in human skeletal muscle, and in particular citrate synthase (CS) activity, has been used a marker of cellular oxidative capacity and mitochondrial density following a training regimen [2, 3]. These enzyme activities are highly adaptable to aerobic training and during exercise a high enzymatic capacity is essential for optimal performance during aerobic exercise [4]. While these characteristics of oxidative enzymes have been known for decades, there is a lack of literature on the relationship between training induced changes in CS activity and whole body $\dot{V}O_{2max}$. The relationship between $\dot{V}O_{2max}$ and CS activity may provide information on whether cardiovascular and local metabolic adaptations are coupled (i.e. do both systems adapt together), and in which subjects or training types does one change more than the other if one is more important to changes in $\dot{V}O_{2max}$ than the other?

A relationship between changes in $\dot{V}O_{2max}$ and changes in CS activity is assumed and often based on observations from classical endurance training (ET) studies with low intensity and long duration. Most of these studies have shown increased CS activity after training [i.e. 5, 6, see Table 1], with seemingly similar effect in both genders (Coggan et al., 1992). In the last decade high-intensity interval training (HIIT) has received wide interest as a time-efficient training modality, using a very high intensity for
\( \dot{V}O_{2\text{max}} \) CS activity in skeletal muscle

a very short duration. HIIT has been shown to increase CS activity in most but not all studies [7-11].

Lower CS activity has been reported in elderly compared to equally active young subjects [12]. This has also been observed in a cross-sectional study where CS activity was lower in both sedentary and active elderly subjects compared to young sedentary and active subjects matched for daily activity by the Baecke questionnaire [13] but with a lower \( \dot{V}O_{2\text{max}} \) per kg fat free mass (FFM) in the elderly subjects [14].

CS activity have been shown to be lower in a group of obese, insulin resistant subjects compared to a group of obese insulin sensitive subjects matched for \( \dot{V}O_{2\text{max}} \) per kg FFM, but in none of the groups an increase in CS activity was seen in response to 6 weeks aerobic endurance training despite increases in \( \dot{V}O_{2\text{max}} \) per kg FFM [15]. Thus, the metabolic state of subject may challenge the relationship between training induced changes in CS activity and in \( \dot{V}O_{2\text{max}} \).

Analysis of CS in skeletal muscle requires relative small biopsy samples (approximately 15 mg w.w.) and the assay has a relatively low inter- and intra assay variation (below 5% in our laboratory), and the analysis can be done on frozen samples. However, methodological variations and differences in preparation of the biopsies between the different studies is a possible concern. CS activity is traditionally analyzed by the methods described by Lowry and Passonneau [16] or by Srere [17]. The latter is based on a reaction between the thiolgroup in acetyl-CoA which react with Ellman’s reagent (5, 5'-dithiobis-(2-nitrobenzoic acid (DTNB)), which is measured spectrophotometrically [17]. The method by Lowry and Passoneau is based on the conversion of malate to oxaloacetate by reduction of \( \text{NAD}^+ \) to \( \text{NADH} \), where the formation of \( \text{NADH} \) is linear to the CS activity [16]. In this method \( \text{NADH} \) may be measured both spectrophotometrically and fluorometrically. Different laboratories use these methods with various modifications, different reagents or temperatures (range: 25-37°C) resulting in possible differences in CS activity between laboratories. Furthermore, the analysis may either be done on untreated tissue (wet weight) or tissue that has been freeze-dried and dissected free of visible connective tissue, blood and adipose tissue (dry weight). Using dry weight ensures that the analysis is done primarily on muscle tissue, and not on adipose or connective tissue, which improves the validity of the result. In addition to the analytical considerations, the time from last exercise bout to the biopsy sampling is of importance. Tonkonogi and colleagues showed that CS activity is increased immediately after acute exercise (30 sec. after cessation of exercise) [18]. This finding was later confirmed in females, but surprisingly not in males [19], which is in contrast to another study including trained and untrained males [20].

In the present review we have collected and compared the previous studies in humans in which CS and \( \dot{V}O_{2\text{max}} \) was measured before and after a training program with the purpose of characterizing the possible relationship between these two variables, and determine which factors that may influence this relationship. Such factors may include the training modality, age, gender, presence of metabolic or other diseases, initial fitness status, and methodological variations. Furthermore, the material allows for a direct comparison of absolute values of CS activity between the different studies with comparable study groups.

Methods

Data sources and search profile

A systematic search of literature on a bibliographical database PubMed published from 1983 to June 2013. We used the search profile: (citrate) AND synthase) AND human) AND skeletal) AND muscle) AND training) NOT electrical stimulation) NOT in-vitro) NOT rats.

Inclusion and exclusion

We included all available studies in which CS activity in skeletal muscle (vastus lateralis) was measured as a marker for improved skeletal muscle oxidative capacity. We limited the search to human studies that included measurements of whole body oxygen uptake (\( \dot{V}O_{2\text{max}} \)) before and after a physical training intervention program. Studies were excluded if the subjects did not complete an incremental \( \dot{V}O_{2\text{max}} \) test to exhaustion. Finally, cross-sectional studies and detraining studies were excluded (Table 1 and Figure 1).
<table>
<thead>
<tr>
<th>Reference</th>
<th>Year</th>
<th>Group number</th>
<th>Group</th>
<th>Group characteristics</th>
<th>n</th>
<th>Gender</th>
<th>Training type</th>
<th>Total time trained (min)</th>
<th>Baseline $\dot{V}O_{2\max}$ (mL·min⁻¹·kg⁻¹)</th>
<th>ΔCS activity (%)</th>
<th>$\Delta \dot{V}O_{2\max}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allenberg et al.</td>
<td>1988</td>
<td>1</td>
<td>DI</td>
<td>Patients with type 2 diabetes</td>
<td>7</td>
<td>Males</td>
<td>ET</td>
<td>2232</td>
<td>N/A</td>
<td>36</td>
<td>7</td>
</tr>
<tr>
<td>Bakkman et al.</td>
<td>2007</td>
<td>2</td>
<td>CON</td>
<td>Healthy young untrained</td>
<td>8</td>
<td>Mixed</td>
<td>ET</td>
<td>480</td>
<td>45</td>
<td>21</td>
<td>40</td>
</tr>
<tr>
<td>Bangsbo et al.</td>
<td>2010</td>
<td>3</td>
<td>CON</td>
<td>Untrained running group</td>
<td>25</td>
<td>Females</td>
<td>ET</td>
<td>1920</td>
<td>33</td>
<td>11</td>
<td>15</td>
</tr>
<tr>
<td>Barnett et al.</td>
<td>2004</td>
<td>4</td>
<td>CON</td>
<td>Untrained football group</td>
<td>25</td>
<td>Females</td>
<td>ET</td>
<td>1920</td>
<td>36</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Berthon et al.</td>
<td>1995</td>
<td>5</td>
<td>OLD</td>
<td>Healthy Elderly</td>
<td>14</td>
<td>Males</td>
<td>ET</td>
<td>1440</td>
<td>35</td>
<td>46</td>
<td>6</td>
</tr>
<tr>
<td>Blomstrand et al.</td>
<td>2011</td>
<td>6</td>
<td>CON</td>
<td>Healthy young sedentary</td>
<td>5</td>
<td>Mixed</td>
<td>HIT</td>
<td>1080</td>
<td>48</td>
<td>29</td>
<td>31</td>
</tr>
<tr>
<td>Burgomaster et al.</td>
<td>2005</td>
<td>8</td>
<td>CON</td>
<td>Healthy young recreationally active</td>
<td>16</td>
<td>Males</td>
<td>ET</td>
<td>720</td>
<td>55</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Burgomaster et al.</td>
<td>2008</td>
<td>9</td>
<td>CON</td>
<td>Healthy young recreationally active</td>
<td>10</td>
<td>Mixed</td>
<td>HIT</td>
<td>1200</td>
<td>41</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>Bylund et al.</td>
<td>1978</td>
<td>10</td>
<td>CON</td>
<td>Healthy young untrained</td>
<td>30</td>
<td>Males</td>
<td>ET</td>
<td>1140</td>
<td>55</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>Carter et al.</td>
<td>2001</td>
<td>11</td>
<td>CON</td>
<td>Healthy young recreationally active</td>
<td>10</td>
<td>Mixed</td>
<td>ET</td>
<td>900</td>
<td>36</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Charifi et al.</td>
<td>2003</td>
<td>12</td>
<td>OLD</td>
<td>Elderly healthy untrained</td>
<td>11</td>
<td>Males</td>
<td>ET</td>
<td>1080</td>
<td>36</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Cox et al.</td>
<td>2000</td>
<td>13</td>
<td>OLD</td>
<td>Elderly healthy untrained</td>
<td>11</td>
<td>Males</td>
<td>ET</td>
<td>1140</td>
<td>55</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>Dawson et al.</td>
<td>1998</td>
<td>14</td>
<td>TR</td>
<td>Young fit</td>
<td>9</td>
<td>Males</td>
<td>HIT</td>
<td>1080</td>
<td>36</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Dubouchaud et al.</td>
<td>2000</td>
<td>15</td>
<td>CON</td>
<td>Healthy young sedentary</td>
<td>9</td>
<td>Males</td>
<td>HIT</td>
<td>1080</td>
<td>36</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Duscha et al.</td>
<td>2012</td>
<td>16</td>
<td>OLD</td>
<td>Obese healthy middle age/elderly</td>
<td>40</td>
<td>Mixed</td>
<td>ET</td>
<td>1140</td>
<td>55</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>Ferketich et al.</td>
<td>1998</td>
<td>17</td>
<td>OLD</td>
<td>Elderly healthy untrained</td>
<td>24</td>
<td>Females</td>
<td>ET</td>
<td>1080</td>
<td>36</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Green et al.</td>
<td>1992</td>
<td>18</td>
<td>CON</td>
<td>Healthy young active but untrained</td>
<td>9</td>
<td>Males</td>
<td>ET</td>
<td>1080</td>
<td>36</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Green et al.</td>
<td>1999</td>
<td>19</td>
<td>CON</td>
<td>Yong healthy with low $\Delta \dot{V}O_{2\max}$</td>
<td>7</td>
<td>Males</td>
<td>ET</td>
<td>1080</td>
<td>36</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Green et al.</td>
<td>2000</td>
<td>20</td>
<td>CON</td>
<td>Healthy young sedentary</td>
<td>10</td>
<td>Males</td>
<td>HIT</td>
<td>1080</td>
<td>36</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Author</td>
<td>Year</td>
<td>Gender</td>
<td>Group Characteristics</td>
<td>Year</td>
<td>Gender</td>
<td>Group Characteristics</td>
<td>Year</td>
<td>Gender</td>
<td>Group Characteristics</td>
<td>Year</td>
<td>Gender</td>
</tr>
<tr>
<td>-------------------</td>
<td>------</td>
<td>--------</td>
<td>-----------------------------------------------</td>
<td>------</td>
<td>--------</td>
<td>-----------------------------------------------</td>
<td>------</td>
<td>--------</td>
<td>-----------------------------------------------</td>
<td>------</td>
<td>--------</td>
</tr>
<tr>
<td>Green et al.</td>
<td>2009</td>
<td>Males</td>
<td>Young healthy</td>
<td>2006</td>
<td>Males</td>
<td>Healthy young sedentary</td>
<td>1997</td>
<td>Males</td>
<td>Healthy elderly</td>
<td>1977</td>
<td>Males</td>
</tr>
<tr>
<td>Gurd et al.</td>
<td>2010</td>
<td>Males</td>
<td>Yong healthy with high ΔVO₂max</td>
<td>2004</td>
<td>Males</td>
<td>Healthy elderly</td>
<td>2000</td>
<td>Males</td>
<td>Healthy elderly</td>
<td>1996</td>
<td>Males</td>
</tr>
<tr>
<td>Harmer et al.</td>
<td>2008</td>
<td>Males</td>
<td>Young healthy active but untrained</td>
<td>2009</td>
<td>Males</td>
<td>Young healthy trained</td>
<td>2011</td>
<td>Males</td>
<td>Young healthy trained</td>
<td>2012</td>
<td>Males</td>
</tr>
<tr>
<td>Heilbronn et al.</td>
<td>2007</td>
<td>Males</td>
<td>Insulin sensitive</td>
<td>1996</td>
<td>Males</td>
<td>Intermittent claudication</td>
<td>1993</td>
<td>Males</td>
<td>Sedentary healthy middle aged</td>
<td>2004</td>
<td>Males</td>
</tr>
<tr>
<td>Howarth et al.</td>
<td>2004</td>
<td>Males</td>
<td>Young healthy</td>
<td>1999</td>
<td>Males</td>
<td>Healthy control</td>
<td>2006</td>
<td>Males</td>
<td>Patients with mtDNA mutations</td>
<td>2012</td>
<td>Males</td>
</tr>
<tr>
<td>Iaia et al.</td>
<td>2009</td>
<td>Males</td>
<td>Young healthy trained</td>
<td>1996</td>
<td>Males</td>
<td>Healthy well trained</td>
<td>1989</td>
<td>Males</td>
<td>Healthy young sedentary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irving et al.</td>
<td>2011</td>
<td>Males</td>
<td>T2DM offspring</td>
<td>2011</td>
<td>Males</td>
<td>Young well trained</td>
<td>1989</td>
<td>Males</td>
<td>Healthy young sedentary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jeppesen et al.</td>
<td>2006</td>
<td>Males</td>
<td>Healthy young sedentary</td>
<td>2011</td>
<td>Males</td>
<td>Healthy elderly</td>
<td>1989</td>
<td>Males</td>
<td>Healthy young sedentary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jeppesen et al.</td>
<td>2012</td>
<td>Males</td>
<td>Healthy matched subjects</td>
<td>2011</td>
<td>Males</td>
<td>Young healthy</td>
<td>2000</td>
<td>Males</td>
<td>Healthy elderly</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kohn et al.</td>
<td>2011</td>
<td>Males</td>
<td>Young well trained</td>
<td>2000</td>
<td>Males</td>
<td>Healthy elderly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lange et al.</td>
<td>2004</td>
<td>Males</td>
<td>Healthy elderly</td>
<td>1997</td>
<td>Males</td>
<td>Healthy young recreational activity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LeBlanc et al.</td>
<td>1999</td>
<td>Males</td>
<td>Healthy young</td>
<td>2011</td>
<td>Males</td>
<td>Active young</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linossier et al.</td>
<td>2000</td>
<td>Males</td>
<td>Healthy young sedentary</td>
<td>1984</td>
<td>Males</td>
<td>Obese</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luden et al.</td>
<td>2009</td>
<td>Males</td>
<td>Healthy young sedentary</td>
<td>1989</td>
<td>Males</td>
<td>Healthy sedentary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MacDougall et al.</td>
<td>2000</td>
<td>Males</td>
<td>Healthy young sedentary</td>
<td>1986</td>
<td>Males</td>
<td>Healthy young</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mandroukas et al.</td>
<td>2001</td>
<td>Males</td>
<td>Healthy young sedentary</td>
<td>1999</td>
<td>Males</td>
<td>Healthy young reproductive activity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Martin III et al.</td>
<td>2000</td>
<td>Males</td>
<td>Healthy young sedentary</td>
<td>1998</td>
<td>Males</td>
<td>Healthy young</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Masuda et al.</td>
<td>2001</td>
<td>Males</td>
<td>Healthy young sedentary</td>
<td>1987</td>
<td>Males</td>
<td>Untrained</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>McKenzie et al.</td>
<td>2000</td>
<td>Males</td>
<td>Healthy young sedentary</td>
<td>1988</td>
<td>Males</td>
<td>Healthy young</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Messonier et al.</td>
<td>2005</td>
<td>Males</td>
<td>Healthy young sedentary</td>
<td>1990</td>
<td>Males</td>
<td>Healthy young</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mogensen et al.</td>
<td>2009</td>
<td>Males</td>
<td>Healthy young</td>
<td>1986</td>
<td>Males</td>
<td>Healthy young</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moore et al.</td>
<td>1987</td>
<td>Males</td>
<td>Healthy young sedentary</td>
<td>1993</td>
<td>Males</td>
<td>Healthy young</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Murias et al.</td>
<td>2011</td>
<td>Males</td>
<td>Healthy young</td>
<td>1992</td>
<td>Males</td>
<td>Healthy young</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ngo et al.</td>
<td>2012</td>
<td>Males</td>
<td>Healthy young</td>
<td>1994</td>
<td>Males</td>
<td>Healthy young</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**VO₂max CS activity in skeletal muscle**
<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Subjects</th>
<th>Sample Size</th>
<th>Age (Mean)</th>
<th>Gender</th>
<th>Training Type</th>
<th>VO\textsubscript{2max} (mL/kg/min)</th>
<th>VO\textsubscript{2max} Difference</th>
<th>VO\textsubscript{2max} Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perry et al.</td>
<td>2008</td>
<td>CON Healthy young recreationally active</td>
<td>8 Males</td>
<td>22</td>
<td>Mixed</td>
<td>HIT</td>
<td>720</td>
<td>45</td>
<td>26</td>
</tr>
<tr>
<td>Perry et al.</td>
<td>2010</td>
<td>CON Healthy young recreationally active</td>
<td>9 Males</td>
<td>24</td>
<td>Mixed</td>
<td>HIT</td>
<td>420</td>
<td>N/A</td>
<td>28</td>
</tr>
<tr>
<td>Putman et al.</td>
<td>1998</td>
<td>CON Healthy young recreationally active</td>
<td>7 Males</td>
<td>26</td>
<td>Mixed</td>
<td>ET</td>
<td>840</td>
<td>45</td>
<td>5</td>
</tr>
<tr>
<td>Randers et al.</td>
<td>2010</td>
<td>CON Young healthy</td>
<td>10 Males</td>
<td>19</td>
<td>Mixed</td>
<td>ET</td>
<td>4992</td>
<td>40</td>
<td>18</td>
</tr>
<tr>
<td>Rud et al.</td>
<td>2012</td>
<td>CON Healthy young sedentary</td>
<td>8 Males</td>
<td>20</td>
<td>Mixed</td>
<td>ET</td>
<td>1960</td>
<td>N/A</td>
<td>14</td>
</tr>
<tr>
<td>Schantz et al.</td>
<td>1983</td>
<td>TR Trained</td>
<td>6 Males</td>
<td>28</td>
<td>Mixed</td>
<td>ET</td>
<td>15840</td>
<td>61</td>
<td>0</td>
</tr>
<tr>
<td>Sjödin et al.</td>
<td>1982</td>
<td>CON Healthy young sedentary</td>
<td>8 Males</td>
<td>23</td>
<td>Mixed</td>
<td>ET</td>
<td>280</td>
<td>N/A</td>
<td>11</td>
</tr>
<tr>
<td>Silvka et al.</td>
<td>2013</td>
<td>CON Young trained</td>
<td>10 Males</td>
<td>22</td>
<td>Mixed</td>
<td>ET</td>
<td>N/A</td>
<td>N/A</td>
<td>11</td>
</tr>
<tr>
<td>Stannard et al.</td>
<td>2010</td>
<td>CON Young healthy untrained</td>
<td>7 Males</td>
<td>21</td>
<td>Mixed</td>
<td>ET</td>
<td>1000</td>
<td>N/A</td>
<td>18</td>
</tr>
<tr>
<td>Starritt et al.</td>
<td>1999</td>
<td>CON Healthy young active but untrained</td>
<td>7 Males</td>
<td>23</td>
<td>Mixed</td>
<td>ET</td>
<td>1000</td>
<td>N/A</td>
<td>19</td>
</tr>
<tr>
<td>Svedenhag et al.</td>
<td>1983</td>
<td>CON Healthy young sedentary</td>
<td>8 Males</td>
<td>24</td>
<td>Mixed</td>
<td>ET</td>
<td>1280</td>
<td>43</td>
<td>62</td>
</tr>
<tr>
<td>Svedenhag et al.</td>
<td>1983</td>
<td>CON Healthy young sedentary</td>
<td>8 Males</td>
<td>25</td>
<td>Mixed</td>
<td>ET</td>
<td>1280</td>
<td>N/A</td>
<td>75</td>
</tr>
<tr>
<td>Talanian et al.</td>
<td>2007</td>
<td>CON Recreational active</td>
<td>8 Females</td>
<td>23</td>
<td>Mixed</td>
<td>ET</td>
<td>280</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
<td>Tarnopolsky et al.</td>
<td>2007</td>
<td>CON Healthy young active but untrained</td>
<td>5 Males</td>
<td>26</td>
<td>Mixed</td>
<td>ET</td>
<td>2100</td>
<td>43</td>
<td>26</td>
</tr>
<tr>
<td>Tiidus et al.</td>
<td>1996</td>
<td>CON Healthy young sedentary</td>
<td>7 Males</td>
<td>28</td>
<td>Mixed</td>
<td>ET</td>
<td>840</td>
<td>48</td>
<td>25</td>
</tr>
<tr>
<td>Tonkonogi et al.</td>
<td>2000</td>
<td>CON Healthy young untrained</td>
<td>6 Females</td>
<td>28</td>
<td>Mixed</td>
<td>ET</td>
<td>840</td>
<td>37</td>
<td>50</td>
</tr>
<tr>
<td>Trappe et al.</td>
<td>2006</td>
<td>CON Recreational active</td>
<td>7 Males</td>
<td>28</td>
<td>Mixed</td>
<td>ET</td>
<td>5460</td>
<td>50</td>
<td>37</td>
</tr>
<tr>
<td>Tynni-Lenné et al.</td>
<td>1999</td>
<td>DI Patients with heart failure</td>
<td>8 Males</td>
<td>29</td>
<td>Mixed</td>
<td>ET</td>
<td>480</td>
<td>18</td>
<td>23</td>
</tr>
<tr>
<td>Vogiatzis et al.</td>
<td>2005</td>
<td>DI COPD patients</td>
<td>10 Mixed</td>
<td>30</td>
<td>Mixed</td>
<td>HIT</td>
<td>1350</td>
<td>N/A</td>
<td>43</td>
</tr>
<tr>
<td>Wibom et al.</td>
<td>1992</td>
<td>CON Health untrained</td>
<td>9 Males</td>
<td>31</td>
<td>Mixed</td>
<td>ET+HIT</td>
<td>900</td>
<td>N/A</td>
<td>40</td>
</tr>
<tr>
<td>Yfanti et al.</td>
<td>2010</td>
<td>TR Moderately trained</td>
<td>10 Males</td>
<td>33</td>
<td>Mixed</td>
<td>ET+HIT</td>
<td>5400</td>
<td>50</td>
<td>54</td>
</tr>
<tr>
<td>Zoll et al.</td>
<td>2005</td>
<td>TR Young healthy trained</td>
<td>9 Males</td>
<td>35</td>
<td>Mixed</td>
<td>ET</td>
<td>2013</td>
<td>64</td>
<td>1</td>
</tr>
<tr>
<td>Østergård et al.</td>
<td>2005</td>
<td>CON Health untrained</td>
<td>19 Mixed</td>
<td>37</td>
<td>Mixed</td>
<td>ET</td>
<td>1350</td>
<td>41</td>
<td>25</td>
</tr>
</tbody>
</table>

All studies and intervention groups included from search. Group column describes categorization in Figure 5: CON; Young healthy sedentary subjects, DI; studies investigating training in patients with various diseases, TR; Endurance trained subjects at inclusion. Group characteristics column: The group as described by the authors. Training type column: ET; The subjects performed endurance training, HIT; The subjects performed high-intense interval training. Inclusion VO\textsubscript{2max} column: N/A; not reported clearly in the study. Baseline VO\textsubscript{2max}: VO\textsubscript{2max} reported before the intervention.
Data extraction

Two authors screened the retrieved articles and relevant studies were independently assessed. One author used a standardized form to extract data; a second author controlled the data for accuracy. Discrepancies were resolved by consensus or third-party adjudication. We constructed tables displaying: First authors, publication year, group characteristics, gender, number of subjects, \( \dot{V}O_{2\text{max}} \) at inclusion, delta CS activity and delta \( \dot{V}O_{2\text{max}} \).

The subjects were characterized as described in the study and the groups were primarily stratified according to men/females, young/elderly, trained/sedentary, healthy/disease (Table 1). If not defined in the article we defined elderly as age above 60 years and trained as a \( \dot{V}O_{2\text{max}} \) above 55 and 50 ml O\(_2\) min\(^{-1}\)·kg\(^{-1}\) for men and women, respectively.

We wanted to study the isolated effect of HIIT and ET, therefore we excluded studies where detraining and resistance training was used [21-24], where spinal cord injuries were studied [25], electrical stimulation was used as stimulation [26], and studies where other muscles (deltoid or triceps brachii) were biopsied and analyzed [23, 27, 28].

Furthermore, we excluded a study if the main estimate for changes in aerobic capacity were Watt\(_{\text{max}}\) [29-32], a time trial [33-35] or time to exhaustion [36]. This was done to allow a comparison of the relative improvement in \( \dot{V}O_{2\text{max}} \) by using the same units for endurance performance.

Some studies only reported pre values of citrate synthase activity and/or \( \dot{V}O_{2\text{max}} \) and hence it was not possible to calculate a relative change [37-41]. Furthermore, 5 studies reported values of CS activity that were more than a factor 10\(^3\) different from other studies, when the unit for CS activity was recalculated to the unit used in the present review, \( \mu \text{mol} \cdot \text{min}^{-1} \cdot \text{g}^{-1} \). We assumed in those cases that the reported unit in the original article was erroneous, but accepted the reported value and included the
data in Figure 2 [6, 42-45]. 5 studies only reported relative changes, and no absolute values of either CS or $\dot{V}O_{2\max}$ pre and/or post the intervention, and these studies were not included in Figure 2. Two studies [46, 47] reported the same results from the same study and Gordon et al. was excluded.

Various terms describing a HIIT training program is used in the included publications (i.e. High Intense Training (HIT), High Intense Interval Training (HIIT), High Intensity Intermittent Exercise (HIIE), and Sprint Training (SIT)). For the purpose of the present review, all of these are termed High Intense Interval Training (HIIT).

Statistics

All statistical analyses were performed in Sigma Plot 12.5 (Systat software, Inc., San Jose, USA). The level of significance was set at $P < 0.05$. For correlations between different variables Pearson’s product moment correlation coefficient ($r$) and corresponding $P$-value were obtained.

Results

Inclusion and exclusion

The literature search identified 180 articles. 110 articles did not meet the inclusion criteria and were excluded. In the remaining 70 articles 149 intervention groups were identified. But 52 intervention groups did not meet the inclusion criteria and were excluded. The main reasons for exclusion were: the groups performed strength training, studied other muscle groups or were control groups. A total of 97 interven-
Absolute CS activity values

There was no relationship between absolute measures of CS and VO$_{2\text{max}}$ when we included all time points ($n = 148$) from studies ($n = 65$) that reported both CS activity as $\mu$mol·min$^{-1}$·g$^{-1}$ (wet or dry weight)$^{-1}$ and VO$_{2\text{max}}$ kg$^{-1}$ ($r = -0.07$, $P = 0.4$, Figure 2). 12 studies including 28 study groups reported CS activity relative to dry weight (freeze dried and dissected free of visible connective tissue, lipids, and blood). CS activity normalized to dry weight (freeze dried and dissected free of visible connective tissue, lipids, and blood). CS activity normalized to dry weight as an isolated factor did not correlate to VO$_{2\text{max}}$ ($r = 0.11$, $P = 0.60$). Neither did the 33 studies with 68 groups that normalized CS activity to wet weight correlate to VO$_{2\text{max}}$ when analysed alone ($r = 0.18$, $P = 0.17$). 20 studies (52 groups) did not report (N/A) clearly how the biopsies were treated prior to analysis, here there was no correlation between CS activity and VO$_{2\text{max}}$ ($r = -0.14$, $P = 0.33$, Figure 2).

Relative CS activity values

The relative changes in VO$_{2\text{max}}$ and CS activity in response to a training intervention in 97 intervention groups (Table 1 and Figure 3) were significantly correlated ($r = 0.45$, $P < 0.001$). The equation for the trend line is: $\Delta$CS = 1.1 $\Delta$VO$_{2\text{max}}$ + 16.8. The significant correlation was present also when all the included study groups were stratified according to training type (Figure 4 and Table 1): ET ($r = 0.42$, $n = 69$, $P < 0.001$), and combined ET and HIIT ($r = 0.81$, $n = 7$, $P < 0.05$), but not with HIIT alone ($r = 0.24$, $n = 21$,
Discussion

There is a clear positive and significant correlation between the relative change in $\dot{V}O_{2\max}$ and in CS activity in response to physical training (Figure 3). There was almost a 1:1 relationship between the relative change in CS activity and change in $\dot{V}O_{2\max}$. Thus, a $9\%$ increase in CS activity may be expected from a $10\%$ increase in $\dot{V}O_{2\max}$. It is noteworthy that this relationship was not present when the correlation analysis was constrained to HIIT training or in elderly subjects alone. Oppositely, the relationship was intact when considering young sedentary subjects, trained subjects, and males alone. Likewise, both endurance training studies and studies combining HIIT and endurance training displayed a significant correlation between changes in $\dot{V}O_{2\max}$ and CS activity. Absolute values of $\dot{V}O_{2\max}$ and CS activity did not correlate, indicating that absolute measures of CS activity cannot be compared across studies and

$P = 0.29$). Stratification according to inclusion background (Figure 5 and Table 1) showed significant correlations in young sedentary subjects ($r = 0.35, n = 63, P < 0.05$), endurance trained subjects ($r = 0.79, n = 9, P < 0.05$), and in patients with various diseases and complications ($r = 0.67, n = 14, P < 0.05$), but not in elderly subjects ($r = 0.20, n = 10, P = 0.57$). By stratification according to gender (Figure 6 and Table 1) only males correlated ($r = 0.63, n = 52, P < 0.001$). In studies using females alone ($r = 0.57, n = 10, P = 0.08$) or groups of mixed gender ($r = 0.31, n = 35, P = 0.07$), there was only a tendency towards a correlation.
Training type (ET and HIIT)

One purpose of this review was to collect and analyze previously published studies in order to determine magnitudes and interrelationships in changes of $\dot{V}O_{2\text{max}}$ and CS in response to ET and HIIT. We found a positive and significant correlation between improvements in $\dot{V}O_{2\text{max}}$ and increases in CS activity in response to endurance training. This finding was not unexpected, but in contrast to this is, the lack of relationship between improvement in $\dot{V}O_{2\text{max}}$ and CS activity in response to HIIT was unexpected. The two forms of training elicited similar average improvements in $\dot{V}O_{2\text{max}}$ (ET: $\approx$ 13% and HIIT: $\approx$ 8%) but ET (\approx 33%) lead to higher improvement in CS activity compared to HIIT (\approx 19%). This underlines the major importance of cardiac performance for maximal oxygen uptake. Since CS activity in skeletal muscle is well correlated with mitochondrial volume in skeletal muscle [2, 3], the lower increase in CS activity with HIIT also indicate that mitochondrial biogenesis may not be stimulated at the same level as ET. In the studies where HIIT did not lead to an increase in CS activity, a significant increase in $\dot{V}O_{2\text{max}}$ was found in two [8, 9] of these five studies [7, 10, 11]. The differences in the CS response may be due a large variation in total training time ranging from 45 min [48] to 3360 min [23] and intensity ranging from 75-95\% HR$_{\text{max}}$ [23] to 150 \% $\Delta\dot{V}O_{2\text{max}}$ [49] in the included HIIT studies. Another factor is that it is
inherent in the nature of HIIT that the time spent training is less than that with endurance training (ET: \(\approx 53\) hr/study vs. HIIT: \(\approx 12\) hr/study in the included studies). The high intensity exercise for a short period may apparently be sufficient to elicit a cardiac adaptation (primarily an increase in maximal cardiac output), but not an adaptation of an important enzyme in the Krebs cycle in skeletal muscle.

On the other hand, the lack of significant relationship between \(\Delta CS\) activity and \(\Delta \dot{V}O_{2\text{max}}\) in the collective HIIT studies may also be due to three distinct studies (no 8, 9, and 23 in Table 1; the 3 triangles in Figure 4 located most low-right) where disproportionate responses were seen. With exclusion of these three studies, a significant correlation is seen \((r = 0.48, n = 18, P < 0.05)\).

Some HIIT studies have been used to induce improvements in endurance performance in already highly trained athletes, measured as time to exhaustion or time trial [10, 50]. But these athletes did not have further increases in \(\dot{V}O_{2\text{max}}\) or CS activity. It is possible that these athletes had already reached a plateau in the metabolic adaptations from the prior ET.

From the data it appears that a 8 wk. HIIT protocol with 3 training sessions per week each consisting of two to six 30 second sprint intervals was a highly time-efficient study [51]. This resulted in a 42% increase in CS activity with a total of 54 min. effective training [51]. Similar improvements in response to HIIT were shown in elderly subjects but after a longer HIIT training period [7]. The largest relative improvement (50-75%) in CS activity was seen in studies with endurance training [5, 21, 52-54]. These stud-
ies are all characterized by a high volume of total training and inclusion of subjects with a relatively low initial whole body \( \dot{V}O_{2\text{max}} \). Even though it is highly speculative, it is possible that the nature of HIIT interventions is too short or extreme to allow mitochondrial biogenesis.

**Ageing**

The expected relationship between improvements in \( \dot{V}O_{2\text{max}} \) and CS activity was not observed in the studies \((n = 10)\) with elderly subjects (Figure 5). A 20% decline in CS activity has been reported with age independent of lifestyle in some studies [14, 55], while others are inconclusive [56]. In contrast, other mitochondrial oxidative enzyme activities, for example the activity of complex I-IV are unaltered [14, 57]. Therefore, it is possible that adaptability in CS activity is altered with aging independently of changes in mitochondrial respiratory capacity, which has also been shown experimentally [57, 58].

A recent study by Duscha and colleagues reports a discrepancy between the relative improvement in CS activity and \( \dot{V}O_{2\text{max}} \) in 3 groups (40-65 years) that performed different amount and intensity (low amount moderate-intensity, low amount-high intensity or high amount-high intensity training) of aerobic training (group # 25-27, Table 1). Only in the group that performed high amount-high intensity training \((r = 0.304, n = 41)\) a positive correlation between relative \( \dot{V}O_{2\text{max}} \) and CS activity was seen (group # 27, Table 1) [43, 58]. Thus, these findings indicate that in middle-aged and elderly a high amount-high intensity training program is necessary for improvement in both CS and Δ \( \dot{V}O_{2\text{max}} \).

**Gender**

We observed that only studies that included males alone showed significant correlation between \( \dot{V}O_{2\text{max}} \), and CS activity. In studies \((n = 10)\) including women alone the relationship was only nearly significant \((P = 0.08)\), which is probably due to lack of statistical power. Is has been suggested [19] that transcriptional, translational, and/or post-translational regulation of CS is different between females and males at rest and immediately after acute exercise. However, this notion is not based on sound physiological considerations, and it remains to be proven.

**Methodological differences: dry or wet weight?**

There was no correlation between absolute values of \( \dot{V}O_{2\text{max}} \) and CS activity in the included studies. The freeze-drying and dissection procedure of the muscle samples should have eliminated some variation due to contamination with non-muscle tissue/cells, but even in these samples, there was no correlation between the absolute values of \( \dot{V}O_{2\text{max}} \) and CS. Although the measurements and analytical variation of \( \dot{V}O_{2\text{max}} \) is well standardized across different laboratories, some day-to-day variation must be expected. Less standardized is the biochemical analysis CS activity. This analysis requires relatively small muscle biopsies, approximately 2-3 mg d.w. corresponding to 10-15 mg w.w. In the authors laboratory CS activity is measured spectrophotometrically as described by Srere [17] at 37°C. The assay has a low inter- and intra assay variation. We find an inter-assay variation of 4.2% in the low range \((27 \pm 1 \, \text{mean} \pm \text{SD}) \mu\text{mol-min}^{-1}\cdot\text{g}^{-1}\,\text{(d.w.)}^{-1}\) and 0.8% in the high range \((613 \pm 5 \, \mu\text{mol-min}^{-1}\cdot\text{g}^{-1}\,\text{(d.w.)}^{-1}\) and an intra-assay variation of 2.5% in the low range \((28 \pm 1 \, \mu\text{mol-min}^{-1}\cdot\text{g}^{-1}\,\text{(d.w.)}^{-1}\) and 4.8% in the high range \((589 \pm 5 \, \mu\text{mol-min}^{-1}\cdot\text{g}^{-1}\text{-protein} \,\text{(d.w.)}^{-1}\) (unpublished data). These are lower than was has been reported for analyses in non-freeze dried and un-dissected tissue (4.9% [34], 5.4% [49] and 7.7% [6] in the low range of CS activity). This speaks for analyzing on dissected tissue. Another major factor for variation in absolute values of CS activity is the analytical temperature (usually 25-37°C), which is, unfortunately, not always reported. Increased activity with 37°C compared to 25°C must be expected. Finally, it would be possible to correct data for blood contamination with e.g. creatine correction or other methods, but this is very seldom reported.

Five studies recruited a non-training control group [43, 50, 59-61]. In these groups no statistical change in Δ\( \dot{V}O_{2\text{max}} \) or ΔCS activity were reported. However, the ΔCS activity reported varies from 10% decrease (NS) [60] to 14% increase (NS) [61]. This indicates that some physiological time related variation should be expected when measuring.

**Responders and non-responders**

Despite a positive correlation between Δ\( \dot{V}O_{2\text{max}} \) and ΔCS activity there is a considerable varia-
tion in the relationship (Figure 3). We have suggested that training regimes, subject background or methodological variation contributes to this. However, it has to be considered that there is a significant inter-subject variation in training induced adaptations in $\dot{V}O_{2\text{max}}$, which increases the variation [62, 63]. The molecular mechanisms underlying the variation in response to exercise training are still poorly understood, but it is possible that also adaptations in CS activity may be individual. A close inspection of Table 1 and Figure 3 reveals that group 23, 31, 42, 48, 63, and 95 reported a negative $\Delta$CS activity.

Limitations

CS activity and $\dot{V}O_{2\text{max}}$ are not always reported both pre and post training. This excluded a large number of studies, and thus removes valuable information. Furthermore, we decided to remove measures of aerobic capacity that was not $\dot{V}O_{2\text{max}}$, but measured as e.g. time trial or Watt max. There is a large variation in how these tests are conducted, which increases the variation in the results between studies. Cross-sectional studies were not taken into consideration. Inclusion of the many cross-sectional studies in the literature may have provided additional information on the absolute values of CS activity across various studies (Figure 2). Finally, the lack of relationship in females and elderly subjects may be due to a low number of included studies studying these groups, which then may have provided a false negative result.

Conclusions

Most factors (young sedentary or trained subjects, males, ET and combined ET and HIIT) showed a positive and significant linear relationship between $\Delta\dot{V}O_{2\text{max}}$ and $\Delta$CS activity. This was not the case in publications studying HIIT, females and elderly subjects. CS activity as a marker of mitochondrial density should be used with care in studies using very short term HIIT. The lack of relationship in the females and maybe also in the elderly is most likely a statistical power problem. Finally, a large methodological variation in the analysis of CS activity between laboratories is probably the major reason for a lack of significant relationship in absolute values in $\dot{V}O_{2\text{max}}$ and CS activity.

Acknowledgements

Regitze Kraunsøe and Katrine Qvist for technical assistance. The financial support from The Nordea Foundation, The Novo Nordisk Foundation, Kathrine and Vigo Skovgaard’s Foundation and Aase and Ejnar Danielsens Foundation. This work is carried out as a part of the research program of the UNIK: Food, Fitness & Pharma for Health and Disease. The Danish Ministry of Science, Technology and Innovation supports the UNIK project.

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

Address correspondence to: Andreas Vigelsø, Center for Healthy Aging, Department of Biomedical Sciences, Panum Institute, building 12.4, Blegdamsvej 3, 2200 N, Denmark. Tel: + 45 35 32 74 23; Fax: + 45 35 32 74 20; E-mail: avhansen@sund.ku.dk

References


VO$_2$max CS activity in skeletal muscle


[31] Little JP, Saafar A, Wilkin GP, Tarnopolsky MA, Gibala MJ. A practical model of low-volume high-intensity interval training induces mitochondrial biogenesis in human skeletal mus-


\[ \dot{V}O_{2\text{max}} \] CS activity in skeletal muscle


[53] Murias JM, Kowalchuk JM, Ritchie D, Hepple RT, Doherty TJ, Paterson DH. Adaptations in...


[75] Green H, Tupling R, Roy B, O’Toole D, Burnett M, Grant S. Adaptations in skeletal muscle exercise metabolism to a sustained session of...


$\bar{V}O_2^\text{max}$ CS activity in skeletal muscle


