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Estimating energy expenditure during front crawl swimming using accelerometers

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Abstract

The determination of energy expenditure is of major interest in training load and performance assessment. Small, wireless accelerometer units have the potential to characterise energy expenditure during swimming. The correlation between absorbed oxygen versus flume swimming speed and absorbed oxygen versus the three axis acceleration recorded on the sacrum, wrist and ankle for swimmers of varying abilities was calculated using Bland-Altman analysis of variance through parallel regression lines fitted for 60 participants, who swam at three different speeds for 6 min duration with 2 min rest times. Swimmers showed a strong positive relationship between VO\textsubscript{2} and RMS acceleration on the wrist (r = 0.77) and ankle (r = 0.73) sensors but not on the sacrum (r = 0.46). The sacrum data was split into elite and novice swimmers, resulting in a strong correlation for elite swimmers and a poor correlation for novice swimmers.

A robust biomechanical technique for the determination of the energy expenditure of swimmers of different categories and genders from acceleration data has been developed.

Keywords: Swimming; energy expenditure; accelerometer; velocity; flume; ANOVA

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1. Introduction

Determining workload during swimming is of importance in relation to recreational swimming in a health perspective and for competitive swimmers in order to quantify training load. Energy expenditure during swimming can be determined directly by measurement of oxygen uptake: Rodriguez F.A. et al. (2000) or indirectly by use of doubly labelled water and heart rate registration: Livingstone M.B.E. et al. (2003). Of these technologies, only heart rate monitors are possible to use on a regular basis in the wet environment. However, there are several drawbacks in using heart rate monitors that have led investigators to try to estimate training load by use of subjective reports of rate of perceived exertion. While swimmers show a high compliance with the prescribed training programme, there is a poor relationship between the coaches and swimmers interpretation of swimming intensity: Stewart A.M. et al. (1997). In addition to the practical problems in using heart rate monitors, it is a problem to quantify the energy expenditure of work performed above the speed that is expected to elicit maximal oxygen uptake, as in for example during interval based training. Thus, new technologies which can precisely determine the energy expenditure during swimming at all speeds are warranted.

For some years, accelerometers have been used to monitor human movement and relate this to the energy expenditure of athletes and the tasks associated with every-day living: Chen K.Y. et al. (1997). More recently preliminary work on the application of accelerometers in monitoring energy expenditure in swimming and on the velocity profiling in freestyle swimming using a purpose-built inertial sensor has been reported: Stamm A. et al. (2012).

Accelerometers can provide accurate timing information for swimmers including stroke rate and lap times, and more recently, the calculation of glide velocity: Stamm A. et al. (2013). The stroke and lap times are determined from features in the acceleration profile: Hagem R.M. et al. (2013). The velocity is determined through filtering and integration of the acceleration data. However, it is unknown if energy expenditure during swimming can be determined by accelerometers. Thus, the aim of the present study is to investigate if accelerations measured during swimming can be related to the energy expenditure determined by direct measurement of oxygen uptake in swimmers of different skill levels (elite, sub-elite, competitive and amateur swimmers). The correlation was calculated using Bland-Altman analysis of variance through parallel regression lines fitted for all participants.

2. Methods

2.1. Swimmer selection

Sixty swimmers (fifteen females and forty-five males) were enrolled in this study. All were required to undertake measurements of weight and height, and to self report age, swimming ability (when known, the 100 m and 400 m times), prior injuries and current weekly exercise regime. The swimming ability was self-ranked as non-swimmer (1), novice (2), recreational (3), competitive (4) and national/elite (5). The swimmers were informed of the reasons for the study and signed a participation consent form. The study was approved by the Griffith University Ethics Committee as project ENG/05/10/HREC.

2.2. Swim details

The swimmer was fitted with the accelerometers using medical tape and asked to both stand vertically and then lie in the horizontal glide position for 5 s to calibrate the accelerometers. The swimmer was fitted with the face mask and commenced the swim trial (Figure 1). Three 6 min swims were interspersed with 2 to 5 min rest periods.

2.3. Acceleration

The acceleration $a_i(t)$ at time $t$ along the $i^{th}$ axis ($i = x, y, \text{and } z$) is given by the equation

$$a_i(t) = g \cos(\theta(t)) + i \cdot a(t) + \omega(t)^2 i \cdot r(t)$$

(1)
where $g$ is the gravitational acceleration, $\theta(t)$ is the time dependent angle between the axis and the vertical direction, $i$ is the unit vector, $a(t)$ is the linear acceleration, and $\alpha(t)$ is the angular velocity of rotation at a distance $r(t)$ from the centre of rotation. The calculation of swim velocity and distance travelled have been demonstrated using accelerometer measurements despite the error and uncertainties involved in the single and double integrations required: Stamm A. et al. (2012).

As energy expenditure can only be related to the dynamic components of acceleration, the gravitation acceleration must be removed. This includes the weight of the feet. For the three orthogonal axes $j = x, y, z$, the root mean acceleration $a_{j,\text{rms}}$ was calculated using a time window of fixed sample length

$$a_{j,\text{rms}} = \frac{1}{n} \sqrt{\frac{1}{n} \sum_{i=1}^{n} (a_{j,i} - \bar{a}_j)^2 - \overline{(\bar{a}_j)^2}} \tag{2}$$

where $a_{j,i}$ is the $i^{th}$ time sample in the $j$ direction, $n$ is the number of samples in the window, and the mean value in the time window is

$$\bar{a}_j = \frac{\sum_{i=1}^{n} a_{j,i}}{n} \tag{3}$$

To reduce window induced fluctuations, the length of the time window was chosen to ensure that more than six strokes were included in the window at the slowest speed. The total acceleration for each unit $A_{tot}$ was calculated by summing the three RMS acceleration values as

$$A_{TOT} = \sqrt{\sum_{j=x,y,z} a_{j,\text{rms}}^2} \tag{4}$$

Equations 1 and 4 were applied to the complete acceleration data set for every swimmer. The steady state RMS acceleration was noted towards the end of every 6 min swim.

2.4. Instrumentation

Following the techniques used in previous swimming investigations with logging accelerometers: Stamm A. et al. (2012), three triaxial accelerometer units: Davey N., et al. (2008), were taped to the swimmer’s sacrum, left wrist and left ankle (Figure 1). By placing one unit as close as possible to the centre of mass, the dynamic effect of body roll on the acceleration measurements is minimised ($r < 40$ mm), however, the gravitational changes will be recorded given the window selected for equation 2. Thus $a_{x,\text{rms}}$ is a measure of body roll. The wrist coordinate system is different to that of Ohgi (2002) who noted maximum acceleration during the in sweep phase and the upsweep and recovery phase. The accelerometer was set to record data at 100 Hz. The RMS window was set to 6 s ($n = 600$). The total flume time required for each swimmer was approximately 30 min. Figure 1 shows the swimming flume, the oxygen consumption unit (Ox) and three accelerometer units located at the left wrist (n1), sacrum (n2) and left ankle (n3), with the orientation of the sensor axes with respect to the human body. In the swimming position, the swimmer moves principally in the $y$ direction for the sacrum unit and the $x$ and $z$ directions for this unit are the mediolateral and the vertical directions respectively.

In the flume, swimmers wore a face mask and a nose plug to ensure the gas analyser recorded the oxygen intake and exhaled breath: Rodriguez F.A. et al. (2008). Oxygen consumption ($\text{VO}_2$) was recorded by a breath-by-breath system adapted for swimming (Quark B2, Cosmed). The steady state $\text{VO}_2$ was taken as the mean value of 41 breaths at the end of each 6 min. The velocity of the water in the flume was controlled and recorded using a calibrated propeller driven sensor. The swimmer was manually timed for 6 min or until the oxygen consumption
had reached a steady state for at least 30 s.

![Fig. 1. Swimming flume, oxygen consumption unit (Ox) and three accelerometer units located at the left wrist (n1), sacrum (n2) and left ankle (n3), with the orientation of the sensor axes with respect to the human body.](image)

3. Results

3.1. Energy expenditure and swim speed

The relation between the oxygen consumption (VO$_2$) and the flume velocity for each swimmer with three swim speeds was determined through multiple regression analysis: Bland and Altman (1995). The analysis of variance for the regression is described in Table 1, and shows how the variability in VO$_2$ can be partitioned into components due to different sources.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degree of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>Variance ratio (F)</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swimmers</td>
<td>46</td>
<td>5.9431e7</td>
<td>1.2919e6</td>
<td>13.97</td>
<td>0</td>
</tr>
<tr>
<td>Velocity</td>
<td>1</td>
<td>1.0584e7</td>
<td>1.0584e7</td>
<td>114.48</td>
<td>0</td>
</tr>
<tr>
<td>Residual</td>
<td>55</td>
<td>8.598e6</td>
<td>9.2451e4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The magnitude of the correlation coefficient $r$ within swimmers is calculated as (Bland and Altman, 1995)

$$r = \frac{S_q}{\sqrt{S_q + \text{Res}}} = \sqrt{\frac{1.0584 \times 10^7}{1.0584 \times 10^7 + 8.598 \times 10^6}} = 0.75$$

(5)

where $S_q$ and Res are the sum of squares and the residual sum of squares, respectively, for the flume velocity from Table 1. A strong positive correlation $r = 0.75$ shows that an increase in the velocity for an individual swimmer was associated with an increased VO$_2$, regardless of the differences between the swimmers.
3.2. Swim speed and total acceleration

An analysis of variance (ANOVA) of the total RMS acceleration at the sacrum, the wrist and the ankle, as a function of energy expenditure (measured as VO₂) was implemented for all swimmers with three swim speeds for each one. Figures 2a and 2b show the ANOVA through parallel regression lines at the wrist and at the ankle. The magnitude of the correlation coefficients using (5) at the wrist is $r = 0.77$, at the ankle is $r = 0.73$, and at the sacrum is $r = 0.46$.

Since the sacrum acceleration data was found to be poorly correlated, the data was split into elite and novice swimmers, in order to identify the trend of the parallel regression lines, defined as having a 100 m swim speed of greater than 1.6 m/s for elite and less than 1.3 m/s for novice. Although the wrist and ankle positions had a strong positive correlation, the elite swimmers showed higher correlation than novice swimmers in both positions. The correlation coefficients and probabilities at the three locations are given in Table 2.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Elite</th>
<th>Novice</th>
<th>Probability Elite</th>
<th>Probability Novice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sacrum</td>
<td>0.9036</td>
<td>0.3722</td>
<td>&lt; 0.0008</td>
<td>&lt; 0.0233</td>
</tr>
<tr>
<td>Wrist</td>
<td>0.9614</td>
<td>0.8252</td>
<td>&lt; 0.0001</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Ankle</td>
<td>0.9414</td>
<td>0.6465</td>
<td>&lt; 0.0001</td>
<td>&lt; 0.0002</td>
</tr>
</tbody>
</table>

A summary of the mean and standard deviation for all acceleration data is given in Table 3. The data from three swims for each swimmer was used to calculate the tabulated mean and standard deviation. All units in m/s².

<table>
<thead>
<tr>
<th>RMS acceleration component</th>
<th>Male (n = 45)</th>
<th>Female (n = 15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sacrum (Atot)</td>
<td>1.25</td>
<td>1.22</td>
</tr>
<tr>
<td>Wrist (Atot)</td>
<td>1.78</td>
<td>1.70</td>
</tr>
<tr>
<td>Ankle (Atot)</td>
<td>2.09</td>
<td>1.78</td>
</tr>
</tbody>
</table>
4. Conclusions

An investigation of the relation between accelerations measured during swimming and the energy expenditure determined by direct measurement of oxygen uptake in swimmers of different skill levels, has been presented in this paper. Triaxial accelerometer sensors placed in the swimmer’s sacrum, left wrist and left ankle were used to record the acceleration of three 6 min swims of each subject.

A strong positive correlation $r = 0.75$ showed that an increase in the velocity for an individual swimmer was associated with an increased VO$_2$. Also, a strong positive correlation coefficient was observed for the wrist and ankle data, however, the sacrum data was poorly correlated. It was necessary to split the data between elite and novice swimmers to establish the relationship for elite swimmers. The total RMS ankle acceleration was larger than the wrist and the sacrum measurements. This occurs because the radius of rotation is largest for the ankle. The $y$ component of the sacrum data (direction of the swim) was found to be the smallest with a mean of 0.23. Craig and Pendergast (1979) reported that the variation in the intra-stroke velocity during free style swimming was $\pm 20\%$. A relatively small and gradual change in acceleration data substantiates this observation.

The determination of the energy expenditure of swimmers of different categories and genders from acceleration data has been developed by an efficient biomechanical technique.

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