IS THERE A RELATIONSHIP BETWEEN RUNNING TECHNIQUE AND RUNNING ECONOMY IN WELL-TRAINED, MIDDLE-DISTANCE ATHLETES?
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Thank you

David Bishop
The purpose of the present study was to investigate if a relationship between running technique and running economy exists in well-trained, middle-distance athletes. Four well-trained, middle-distance athletes performed a 15-minute exercise protocol on a treadmill, running at velocities 16.1, 17.6, 19.3 km.h⁻¹ for 5 minutes each without recovery. Oxygen uptake was measured and the subjects were video recorded throughout. Subjects’ ground contact time, stride frequency and stride length was calculated via the video recording. Immediately prior to the treadmill test, subjects performed a jumping test to attain a reactive strength index. Two values of running economy were calculated. The first was $\bar{\text{V}}\text{O}_2$ at 16.1 km.h⁻¹, and the second was relative change in $\bar{\text{V}}\text{O}_2$ with increasing running economy, thought to be more correlated to performance in well-trained middle-distance athletes. Following a Pearson’s product moment correlation analysis, a significant (P<0.01) correlation was only observed between ground contact time and running economy, expressed as the relative change in $\bar{\text{V}}\text{O}_2$ with increasing running velocity. Strong correlations were also observed between reactive strength index and running economy ($r=-0.7$), expressed as $\bar{\text{V}}\text{O}_2$ at 16.1 km.h⁻¹, and stride frequency and running economy ($r=0.62$), expressed as an increase in $\bar{\text{V}}\text{O}_2$ relative to increasing running velocity. It was concluded that running technique is more strongly correlated to running economy, when expressed as the relative change in $\bar{\text{V}}\text{O}_2$ with increasing running velocity, predominantly through the technique parameter, ground contact time. It is thought that this is due to greater leg stiffness and a greater utilisation of elastic energy stored in the stretch shortening cycle. Foot-striking patterns may also have contributed. Future research should be directed towards methods of optimising ground contact time to increase running economy and middle-distance running performance.
CHAPTER I: INTRODUCTION
Foster and Lucia (2007) stated that running performance depends on maximal oxygen uptake, the ability to sustain a high percentage of this maximal oxygen uptake for an extended period of time and running economy. Running economy has been defined as the relative energetic cost of running, or more recently, the energy demand for a given velocity of sub maximal running (Saunders et al. 2004). That is, with a higher running economy, running at a certain speed costs less energy than it would with a lower running economy. This is obviously beneficial in running performance, where the lower the energy cost of a certain speed, the longer that speed can be maintained for.

Although VO$_{2\text{max}}$ has been suggested a good predictor of success in endurance events, it has been known for some time that the winner of an endurance event cannot be predicted from $\dot{V}O_2$$_{\text{max}}$ (Costill, 1970). This suggests that good performance in endurance athletics requires more than a high VO$_{2\text{max}}$ and this is evidenced in a recent study; Elite black Eritrean distance athletes were compared to elite white Spanish distance athletes. The $\dot{V}O_2$$_{\text{max}}$ values of both groups were not shown to be significantly different, yet the Eritrean group’s performance was of a higher standard. The authors concluded that the performance difference resulted from the Eritreans’ superior running economy (Lucia et al. 2006). Despite this obvious importance of running economy to running performance there have been surprisingly few studies on strategies to improve running economy (Foster and Lucia, 2007).

It has been shown that individuals trained in endurance running have a higher running economy than their untrained counterparts (Bransford and Howley, 1977) and more recently it has been shown that strength-trained endurance athletes have a higher running economy (Paavolainen et al., 1999). Thomas et al. (1995) found that various physiological parameters were associated with changes in running economy. During a 5-km race involving trained athletes running between 80-85% $\dot{V}O_2$$_{\text{max}}$, a decline in running economy was correlated with minute ventilation and higher core temperature (Thomas, Fernhall and Grant, 1999). The study concluded that the effect of increased circulation, and higher ventilatory rates and body temperatures were responsible for the
observed impairments in running economy. Tendon stiffness and muscle fibre type
distribution have also shown influence on running economy (Armstrong and Laughlin,
1985; Arampatzis et al., 2006; Denadai et al., 2006). Arampatzis et al. (2006) showed
that runners exhibiting a greater running economy possessed higher normalised tendon
stiffness. The authors speculated that at low level forces, a more compliant tendon will
increase the force potential of the muscle while running and therefore the volume of
active muscle at a given force generation will increase. Rolf et al. (1997) took muscle
biopsies from a group of elite orienteer’s and found that the most economical possessed a
higher content of type I muscle fibres in the major muscle groups of the lower
extremities. However, in contrast, Larsen (2003) compared two groups of elite runners,
Kenyan and Caucasian. Whilst there were significantly different average running
economies between the two groups, muscle fibre type distribution was not shown to be
significantly different. Flexibility has also been shown to correlate with running
economy. Jones (2002) tested international male distance runners for running economy
and flexibility and found that the most economical runners were also the least flexible,
suggesting their stiffer musculotendinous structures reduce the aerobic demand of sub
maximal running by facilitating a greater elastic energy return during the shortening
phase of the stretch-shortening cycle.

The effect of running technique on running economy has received relatively little
research (Foster and Lucia, 2007). Kyröläinen, Belli and Komi (2001) attempted to
explain the effect of biomechanical factors on intraindividual differences in running
economy and although the lower performances in running economy were suggested to be
related to poor running technique, such as unusually high braking forces, no conclusive
results were obtained. Another study by Heise and Martin (2001) found that recreational
runners that produced a greater ground reaction force were less economical, suggesting
that wasteful vertical motion increased the energetic cost of running at the fixed velocity.
However Nummela et al. (2007) performed a study on trained endurance athletes and
found no significant relationship between ground reaction force and running economy,
but did find a relationship between short contact time (that is, the time the foot remains in
contact with the ground on each step) and running economy. It has been suggested the
critical point in economical running is the speed lost during the point braking phase (Mero, Komi and Gregor, 1992), that is, the impact of the foot coming into, and remaining in, contact with the ground during running. This would suggest that a shorter contact time would reduce the energetic cost of this breaking phase, making running more economical.

Chen et al. (2007) suggested that during downhill running, the reduction observed in running economy may be due a lower stride frequency and shorter stride length. A reduction in stride frequency has been suggested to be related to decreased stiffness of the propulsive leg in running (Braun and Dutto, 2003). In addition, a reduction to stride frequency has been shown to be significantly linked to increased ground contact time (Nummela et al., 2007). The global alteration of running technique, including the reduction of stride length and stride frequency, was shown to increase the oxygen cost of sub-maximal running in sub-elite tri-athletes (Dallam et al., 2005). However, in contrast, reduction to stride length has been shown to correlate with an increase in running economy (Collins et al., 2000).

The term running technique can be applied to a whole context of biomechanical variables. However, in the light of the current research, it would seem that the running technique parameters contact time, stride frequency and stride length seem to most accurately represent the term running technique, especially with reference to effectors of running economy. Therefore the present study defined running technique with the parameters contact time, stride frequency and stride length.

It is clear that the limited literature regarding effect of running technique on running economy is contradictory and inconclusive. The aim of the present study is to investigate if a relationship between running economy and running technique exist. If a relationship is found, it will provide the foundations for future research to discover the optimum ways to improve running technique to provide maximum performance in middle-distance running.
The hypothesis for the present study was that a relationship between running technique and running economy does exist in well-trained, middle-distance athletes.
CHAPTER III: METHODOLOGY
Subjects

Four well-trained male middle-distance athletes (one 800m runner, two 1500m runners and one 5000m runner) volunteered as subjects for the present study. All subjects had either represented Great Britain, England, Wales or Scotland at age group level or had medalled at a national championship. Mean ± SD age, height and body mass were: 21.25 ± 0.96 years, 1.85 ± 0.05 m, 69.75 ± 3.94 kg respectively. All the subjects were fully informed of the procedures and the possible risks associated with the study and written informed consent (see appendix) was taken from each subject. The informed consent was in accordance with the guidelines of the Ethical Committee of the University of Wales Institute, Cardiff.

Procedures & Measurements

In order to measure the subjects’ running economy, each subject performed a 15 minute exercise protocol on a treadmill with a positive gradient of 1%, as this has been suggested to best represent the energetic cost of running outdoors (Jones and Doust, 1996). The exercise protocol involved subjects running at three different velocities for 5 minutes each, continuously, immediately following a warm up. The velocities were 16.1, 17.6 and 19.3 km.hr⁻¹, equivalent to 6:00/mile, 5:30/mile and 5:00/mile as these paces were suggested by Daniels (1999) to be ideal training paces across the three continuous running zones: easy, steady and threshold running, based on the mean 1500m best race time of the subjects (3 minutes and 50 seconds). The warm up pace was 7:30/mile as this pace has been suggested to best increase blood flow with minimal muscle stress and damage in well-trained runners (Noakes, 2005). Throughout the treadmill run, oxygen consumption was measured using the breath-by-breath function on Oxycon Pro (Oxycon pro, Erich Jaeger, LA Bunnick, The Netherlands). The Oxycon Pro system was volume calibrated to atmospheric conditions and the subjects were fitted with an oxygen mask which was connected to the Oxycon system.

Subjects’ running technique data was collected whilst the subjects were performing the treadmill exercise protocol. The subjects’ entire time on the treadmill was video-recorded using a standard 50Hz video camera (Sony DSR-PD100AP DVCAM camcorder, Sony
Electronics Inc., New Jersey, USA). The camera was set up on a tripod, approximately 1 metre to the right hand side of where the subjects would be running, with the tripod always set up to maximum height so as to standardise procedure. Subjects were also required to perform a jumping exercise to attain the subjects’ reactive strength index, an accurate predictor of stretch-shortening cycle ability (Hore, 2004). Subjects were instructed to perform a maximal squat jump with countermovement, followed immediately by 4 subsequent squat jumps, trying to reduce contact time and maximise flight time, on a force plate (Smartspeed, Fusion Sport, Brisbane, Australia). The force plate calculated the reactive strength of each jump by calculating the jump height (mm) divided by contact time (ms), giving 4 reactive strength index values per jump trial (one for each subsequent jump after the initial squat jump). This process was done 4 times, with the first being a practise trial to standardise technique and the remaining three trials being used to give a final score. This was achieved by averaging the three greatest reactive strength index values within each trial, to give an average reactive strength index for each jump trial. These three reactive strength index values were then averaged to give an overall reactive strength index value for the subject. This process is illustrated for a typical subject (DBI) in Table 1. To standardise the procedures, subjects were required to place their hands on their hips, creating a ‘belt’ using their thumb and fingers, and to hold them there for the entire duration of the jumping trial (Figure 1). This eliminated the effect of arm swing, which eradicated the effect of upper extremity strength on the results.

Figure 1. The hand position required by the subjects, standardising procedure by eradicating arm swing effect.
Table 1. The calculation of a reactive strength index for a typical subject (DBI).

<table>
<thead>
<tr>
<th>Jump</th>
<th>Trial</th>
<th>Average of best 3 trials</th>
<th>Subject's Overall RSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1b</td>
<td>2.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1c</td>
<td>1.56</td>
<td>2.24</td>
<td></td>
</tr>
<tr>
<td>1d</td>
<td>2.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1e</td>
<td>2.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2a</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2b</td>
<td>2.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2c</td>
<td>2.79</td>
<td>2.56</td>
<td>2.46</td>
</tr>
<tr>
<td>2d</td>
<td>2.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2e</td>
<td>2.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>2.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3c</td>
<td>2.55</td>
<td>2.59</td>
<td></td>
</tr>
<tr>
<td>3d</td>
<td>2.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3e</td>
<td>1.23</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Data Analysis

Two values for running economy were obtained for comparison, the first was a value expressed as the subjects’ average $\dot{V}O_2$ at 16.1 km.hr$^{-1}$ and the second was a value expressed as the change in the subjects’ $\dot{V}O_2$ with increasing running velocity, such that the value represented the additional ml.min$^{-1}$ increase to the rate of oxygen consumption by the subject, with each 1 km.hr$^{-1}$ increase to running velocity. The first value for running economy is generally accepted to correlate strongly to distance running performance in human runners (McArdle, Katch and Katch, 2005). However, it has been suggested that due to the majority of middle-distance athletes’ training being performed at this intensity and higher, it may not correlate as strongly with their running performance (Abe et al., 1998; Weston, Mbambo, and Myburgh, 2000). Therefore the present study will also measure running economy expressed as the second method, which it is thought may be better correlated to running performance in well-trained middle distance runners (Martin and Coe, 1997). To acquire these two running economy values, each subject’s breath-by-breath oxygen consumption was averaged across 30s intervals throughout the entire protocol. This gave 4 values for the last 2 minutes of each exercise stage (this was not applied to the warm up running velocity) which were averaged to give an average rate of oxygen consumption for each exercise stage. This process is illustrated for a typical subject in Table 2. The three average $\dot{V}O_2$ values were then plotted against running velocity, in km.hr$^{-1}$, on a scatter diagram and a linear trend line was fitted using Microsoft excel (Excel 2007, Microsoft Inc., New Mexico, USA), as shown in Figure 2, for the same subject as in Table 2. The gradient of the trend line, 2.39 in this example, represents the relationship between $\dot{V}O_2$ and running velocity in the subject, such that for every 1 km.hr$^{-1}$ increment in running velocity, an additional 2.39 ml.kg$^{-1}$.min$^{-1}$ of oxygen are consumed. This gradient was then multiplied by subject body mass in kg (72.3 kg for subject used in table 2 and figure 2) to define the subjects’ absolute running economy, as ml.min$^{-1}$.km.hr$^{-1}$. Therefore, the running economy, expressed as an increment of $\dot{V}O_2$ across the three running velocities, of the subject (RBU) used as an example would be 172.8 ml.min$^{-1}$.km.hr$^{-1}$.
Table 2. The calculation of an average $\dot{V}O_2$ over the last 2 minutes of each running velocity stage, for a typical subject (RBU).

<table>
<thead>
<tr>
<th>Running Velocity (km.hour$^{-1}$)</th>
<th>Stage Time (min ss)</th>
<th>$VO_2$ (ml.kg$^{-1}$.min$^{-1}$)</th>
<th>Average $VO_2$ (ml.kg$^{-1}$.min$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.1</td>
<td>03:30</td>
<td>53.3</td>
<td>53.425</td>
</tr>
<tr>
<td></td>
<td>04:00</td>
<td>53.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>04:30</td>
<td>53.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>05:00</td>
<td>52.6</td>
<td></td>
</tr>
<tr>
<td>17.6</td>
<td>03:30</td>
<td>58.4</td>
<td>58.65</td>
</tr>
<tr>
<td></td>
<td>04:00</td>
<td>58.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>04:30</td>
<td>58.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>05:00</td>
<td>59.6</td>
<td></td>
</tr>
<tr>
<td>19.3</td>
<td>03:30</td>
<td>57.7</td>
<td>61.125</td>
</tr>
<tr>
<td></td>
<td>04:00</td>
<td>63.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>04:30</td>
<td>63.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>05:00</td>
<td>59.5</td>
<td></td>
</tr>
</tbody>
</table>

The other value for running economy was simply the average $\dot{V}O_2$ over the last 2 minutes of the stage ran at 16.1 km.hr$^{-1}$. This is also shown in table 1, where the running economy value, expressed as $\dot{V}O_2$ at 16.1 km.hr$^{-1}$, for that particular subject would be 53.43 ml.kg$^{-1}$.min$^{-1}$. 
Figure 2. The calculation of running economy when expressed as an increment in $\dot{V}O_2$ across the three running velocity stages, for a typical subject (RBU).

The video footage containing the technique data was downloaded from the video camera using the play back function onto Silicon Coach Pro (Silicon Coach Pro, Silicon Coach, Dunedin, New Zealand) where the last 30 seconds of every stage was cut and analysed for contact time, stride length and stride frequency. The subjects’ contact time was acquired by counting the amount of frames the subjects’ left foot was in contact with the ground. This was done over the first 10s of the last 30s of each running velocity stage and then results were averaged, giving three values of ground contact time, one for each running velocity stage. The data was collected using a 50Hz camera; this meant that there were 50 frames in a second. Therefore, the average number of frames the foot was in contact with the ground was divided by 50 to convert the data from frames to seconds.

Stride frequency was calculated by counting the number of frames in a stride, which was defined as the moment the left foot came into contact with the ground through until the moment the left foot came into contact with the ground once more. This was done to the nearest stride over 500 frames. Table 3 shows how this process was done for a typical subject. These were then averaged to give an average amount of frames per stride. 500
(due to 500 frames equating to 10s) was then divided by the average frames per slide value which was then multiplied by 6 to give strides per minute value. This was done over all three exercise stages, giving three values for stride frequency.

Table 3. The calculation process of average stride frequency for a typical subject. In this example, the velocity was 16.1 km.hr\(^{-1}\).

<table>
<thead>
<tr>
<th>Frames per stride</th>
<th>Running Velocity (km.hr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16.1</td>
</tr>
<tr>
<td></td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>37</td>
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<td></td>
<td>37</td>
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<td>37</td>
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<td></td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>38</td>
</tr>
<tr>
<td>Average frames per stride</td>
<td>37.13</td>
</tr>
<tr>
<td>Seconds per stride</td>
<td>0.74</td>
</tr>
<tr>
<td>Strides per minute (stride frequency)</td>
<td>80.79</td>
</tr>
</tbody>
</table>

Stride length was calculated using a simple ‘distance = speed x time’ model. The speed of each exercise stage was worked out in metres per second and this value was divided by the number of strides taken in a minute (the subject’s calculated average stride frequency) to give an average stride length, in metres. As with contact time and stride frequency, there were three values for stride length. For investigating a relationship between running
economy expressed as $\dot{V}O_2$ at 16.1 km.hr$^{-1}$ the values of average contact time, stride frequency and stride length at the 16.1 km.hr$^{-1}$ running velocity stage was used. However, when investigating a relationship between running economy, expressed as the relationship between $\dot{V}O_2$ and running velocity, the three values of average contact time, stride frequency and stride length, were plotted on a scatter diagram against running velocity and a linear trend line was fitted. The gradient of this linear trend line represented the relationship between the technique parameter and running velocity, such that for every 1 km.hr$^{-1}$ increase to running velocity, ground contact time decreased and stride frequency and length increased, by the gradient of their trend line (in seconds). This process is illustrated in Figure 3 for ground contact time in a typical subject (TMA). The gradient of the line, -0.008 represents the reduction, in seconds, of contact time for each 1 km.hr$^{-1}$ increase in running velocity.
Figure 3. The calculation of ground contact time as an expression of its relationship with running velocity. The gradient of the trend line, -0.008, represents the value used for contact time, in sec.(km.hr⁻¹).

Statistics
The relationship between stride length, stride frequency, contact time, jump characteristics and running economy was investigated using a standard Pearson product moment correlation and linear regression analyses. These values were then referred to a table of critical values (see appendix) where the P value was determined. Values are expressed as mean ± standard deviation. All statistical analyses were undertaken using the Data Analysis tool on Microsoft Excel (Excel 2007, Microsoft Inc., New Mexico, USA).
CHAPTER IV: RESULTS
Running Economy

A typical set of data for a subject’s (RBU) average oxygen consumption across the last 30 seconds of each of the three exercise stages (not including the warm up) is shown in figure 2. The straight line is the best fit linear trend line for the data, where the gradient represents the relationship between the subject’s $\dot{V}O_2$ and running velocity in km.hr$^{-1}$. This figure was then multiplied by the subject’s body mass to give a definition of running economy, as shown, for all subjects, in table 4.

Table 4. The calculated running economy, expressed as change in $\dot{V}O_2$ with increasing velocity, of each subject. The gradient of the trend line of each subject’s average oxygen consumption for the last 30s of each exercise stage was multiplied by the body mass of that subject to give a value of running economy in ml.min$^{-1}$. (km.hr$^{-1}$)$^{-1}$.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Gradient of Linear Trend Line</th>
<th>Body Mass (kg)</th>
<th>Running Economy (ml.min$^{-1}$.km.hr$^{-1}$)$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBI</td>
<td>3.94</td>
<td>68.1</td>
<td>268.31</td>
</tr>
<tr>
<td>TMA</td>
<td>4.73</td>
<td>65</td>
<td>307.45</td>
</tr>
<tr>
<td>CGO</td>
<td>4.26</td>
<td>73.6</td>
<td>313.54</td>
</tr>
<tr>
<td>RBU</td>
<td>2.39</td>
<td>72.3</td>
<td>172.80</td>
</tr>
</tbody>
</table>

There was a considerable variation in running economy across the 4 subjects, despite them being of a similar population (that is, all well-trained, middle-distance athletes), (mean ± standard deviation = 265.52 ± 64.98 ml.min$^{-1}$.km.hr$^{-1}$)$^{-1}$ and this is shown in Figure 4.
Figure 4. Results for all subjects across the entire exercise protocol. As in Figure 2, the straight line is a linear trend line of each subject’s average VO₂ over the last 30 seconds of each running velocity. The trend line equation and R² value are only presented for a typical subject (DBI), however, all subjects’ trend line equation and R² value were calculated.

The subjects’ running economy, expressed as VO₂ at 16.1 km.hr⁻¹, is shown in table 5. Running economy expressed in this way was shown to be strongly correlated (r=0.81) to running economy expressed as the change in VO₂ with increasing running velocity, however a significant relationship was not observed.

Table 5. The running economy of the subjects’ when expressed as VO₂ at 16.1 km.hr⁻¹.

<table>
<thead>
<tr>
<th>Subject</th>
<th>VO₂ (ml.kg⁻¹.min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBI</td>
<td>50.975</td>
</tr>
<tr>
<td>RBU</td>
<td>53.425</td>
</tr>
<tr>
<td>TMA</td>
<td>53.875</td>
</tr>
<tr>
<td>CGO</td>
<td>58.325</td>
</tr>
</tbody>
</table>
Running Technique

In addition to the running economy of the subjects, considerable variation in ground contact time was also observed, as shown in figure 5. Ground contact time, expressed as the change in ground contact time with increasing running velocity, was shown to be significantly (P<0.05) correlated (r=0.95) to running economy when expressed as change in \( \dot{VO}_2 \) with increasing running velocity. However, contact time, expressed in seconds, was observed to be only weakly correlated (r=0.11) to running economy, expressed as \( \dot{VO}_2 \) at 16.1 km.hr\(^{-1}\).

![Figure 5](image.png)

**Figure 5.** The variation in the average ground contact times for each running velocity between subjects. The equation of the trend line and R\(^2\) value are only presented for one subject, however all subjects’ trend line equation and R\(^2\) value were calculated.

Large variations in stride length and stride frequency were also observed, the findings are illustrated in Figures 6 and 7. Both stride characteristics were seen to increase with increasing speed. Stride frequency and stride length, expressed as change with increasing running velocity, were observed to be strongly related (r=0.62, 0.4, respectively), but a significant relationship was not observed.
Figure 6. Stride Length variability in subjects across the three running velocities.

Figure 7. Stride frequency variability in subjects across the three running velocities.

Both stride frequency and stride length, when expressed as values at 16.1 km.hr\(^{-1}\), were shown to be very weakly correlated to running economy when expressed as \(\dot{V}O_2\) at 16.1 km.hr\(^{-1}\). No significant relationships were observed between reactive strength index and running economy, however, reactive strength index was shown to be more strongly
correlated to running economy expressed as $\dot{V}O_2$ at 16.1 kph rather relative change in $\dot{V}O_2$ with increasing running velocity ($r=-0.7$ and 0.26, respectively), being strongly negatively correlated to running economy at 16.1 kph. Stride frequency was observed to also be negatively correlated to running economy expressed as $\dot{V}O_2$ at 16.1 kph, albeit weakly ($r=0.06$).


Denadai, B., Ortiz, M., Greco, C., de Mello, MT. (2006) Interval training at 95% and 100% of the velocity at VO2 max: effects on aerobic physiological indexes and running performance. *Applied Physiology, Nutrition and Metabolism* 31(6): 737-43


APPENDIX A

EXAMPLE OF INFORMED CONSENT SHEET – SEE ATTACHED

APPENDIX B

ETHICS APPROVAL DOCUMENTS – SEE ATTACHED

APPENDIX C

TABLE OF CRITICAL VALUES – SEE ATTACHED
APPENDIX D

EQUIPMENT PRODUCT INFORMATION

**Video Camcorder**

DSR-PD100AP DVCAM camcorder, Sony Electronics Inc., New Jersey, USA.

**Smart Speed Jump Matt**

Smartspeed, Fusion Sport, Brisbane, Australia

**Oxycon**

Oxycon pro, Erich Jaeger, LA Bunnick, The Netherlands

**Silicon Coach**

Silicon Coach Pro, Silicon Coach, Dunedin, New Zealand

**Excel 2007**

Microsoft Excel 2007, Microsoft Inc. , New Mexico, USA.