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

David Bishop
ABSTRACT

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.hr⁻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 $\dot{V}O_2$ at 16.1 km.hr⁻¹, and the second was relative change in $\dot{V}O_2$ 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 $\dot{V}O_2$ with increasing running velocity. Strong correlations were also observed between reactive strength index and running economy ($r=-0.7$), expressed as $\dot{V}O_2$ at 16.1 km.hr⁻¹, and stride frequency and running economy ($r=0.62$), expressed as an increase in $\dot{V}O_2$ 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 $\dot{V}O_2$ 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 VO$_{2\max}$ (Costill, 1970). This suggests that good performance in endurance athletics requires more than a high VO$_{2\max}$ and this is evidenced in a recent study; Elite black Eritrean distance athletes were compared to elite white Spanish distance athletes. The VO$_{2\max}$ 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. This may be due to a lack of knowledge in the factors associated with 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% VO$_{2\max}$, 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 II: LITERATURE REVIEW
Running Economy

It is well known that running performance depends on a complex interplay of factors (Joyner, 1991). Of these factors, running economy is one of the most important factors in determining and improving distance running performance (Morgan et al., 1989; Saunders et al., 2004). Running economy can be defined as the oxygen cost of running at a fixed speed (McArdle, Katch and Katch, 2006). An athlete with a greater running economy will have a smaller rate of oxygen consumption whilst running than an athlete with a lesser running economy, running at the same pace. The obvious benefit of this is that with a greater running economy, athletes will be able to run at greater velocities for longer.

Many studies have suggested the importance of running economy on endurance performance (Costill et al., 1971; Bransford and Howley, 1977; Conley and Krahenbuhl, 1980; Foster and Lucia, 2007). Running economy has been measured in trained and untrained men and women, where subjects performed a series of treadmill tests during which VO$_2$ was measured at sub maximal work loads (Bransford and Howley, 1977). The results of the study indicated that VO$_2$ increased linearly on the treadmill within any range of speeds, regardless of sex or training. The authors stipulated that the lowered cost of running along with a greater maximal aerobic power was a main determinant of endurance performance. This was in agreement with such studies as Costill et al. (1971), who suggested that a low oxygen cost of running and a well-developed aerobic capacity are two factors which contribute to successful endurance performance and Conely and Krahenbuhl (1980) who stipulated that running economy accounts for a large and significant amount of the variation in performance of an endurance race. The suggested importance of running economy over other variables such as the rate of maximal oxygen uptake and lactate threshold was furthered in a study by Lucia et al. (2006). Seven elite black Eritrean distance runners were compared against a control group of nine elite white Spanish distance runners. Running economy, along with rate of maximal oxygen consumption and main anthropometric characteristics were determined. Although the VO$_2_{max}$ of the two groups was not statistically different, running economy of the Eritrean athletes was significantly lower. They authors went on to suggest that superior running
economy rather than enhanced VO2max, may be the common denominator in the success of black endurance runners of east African origin.

Running economy, within the current literature, has generally been assessed by measuring VO2 at a fixed running speed, generally 16.1 km.hr\(^{-1}\), as this has been shown to correlate strongly to distance running performance in humans (McArdle, Katch and Katch, 2005). However, there has been a lack of research in this area using well-trained, middle distance runners and within the limited research, it has been suggested that due to the majority of their training being performed at this intensity and higher, it may not correlate as strongly with performance as strongly (Abe et al., 1998; Weston, M bambo and Myburgh, 2000). Weston, Mbambo and Myburgh (2000) showed that amongst elite Kenyan distance runners, VO2 at 16.1 km.hr\(^{-1}\) was not correlated to 10-km performance. It has been suggested that a range of higher running velocities may be more suited in the assessment of running economy for well-trained middle-distance runners (Martin and Coe, 1997). This has been evidenced in a study by Lucia et al. (2006), who observed correlations between running economy, expressed as VO2 at 17, 19 and 21 km.hr\(^{-1}\), and distance running performance, amongst elite Spanish and Eritrean middle- and long-distance runners.

The current literature suggests that running economy is beneficial to endurance performance and it is therefore sensible to conclude that in order to maximise endurance performance, athletes and coaches should attempt to maximise running economy. To achieve this, knowledge of the factors that contribute to firstly, the intraindividual differences in running economy and secondly, the ways of improving running economy are required (Martin and Coe, 1997; Foster and Lucia, 2007). A number of factors have been suggested to explain the intraindividual differences in running economy, including physiological and anthropometric factors such as body mass and size, leg spring, tendon stiffness, tendon elasticity and running technique factors, such as stride length, stride frequency and contact time.
Physiological & Anthropometric Variables

It has been shown that more economical runners are generally smaller in stature and body mass that less economical runners (Saltin et al., 1995; Lucia et al., 2007). Often, these studies compare elite eastern African runners to a control group (Saltin et al., 1995; Lucia et al., 2007). It has also been suggested that lower leg width is related to running economy. Lucia et al. (2007) demonstrated a significant inverse correlation between the maximal circumference of the calf and the VO\textsubscript{2} at a fixed running speed. This is evidenced in theory, as adding weight will mean more energy required to create motion, that is, adding to the energy cost of motion.

Heise and Martin (1998) investigated the leg spring characteristics and the aerobic demand of running. They found that runners with a lower running economy possess a more compliant running style during ground contact, which the authors suggested meant greater force demands on extensor musculature, therefore reducing running economy through firstly, an increased rate of fatigue in the affected muscles and secondly, a heightened metabolic cost of the additional, non-beneficiary movement. This is in agreement with further literature which showed the more economical runners to have a greater contractile strength and higher normalised tendon stiffness (Arampatzis et al., 2006). This suggests the runners’ force potential (that is, the muscle’s ability to generate force) of the muscle will increase whilst running and therefore the volume of active muscle at a given force generation will decrease, leading to a greater efficiency. Furthermore, studies have shown strength training improves running economy through improvements in neuromuscular characteristics (Paavolainen et al., 1999a; Nummela et al., 2006) which further supports the theory that a high contractile strength contributes to a higher running economy. In fact, Paavolainen et al. (1999a) found a significant relationship between increasing explosive strength and running economy (due to the subsequent decrease in contact time).

Much research has been directed to a possible relationship between the stretch-shortening cycle and running economy. The stretch-shortening cycle, is an eccentric contraction followed by an immediate concentric contraction of the same muscle (Sewell, Watkins
and Griffin, 2005). It has been suggested that elastic structures aligned with the contractile component of a joint movement (that is, the muscle) can store energy ‘like a spring’ after being forcibly stretched (Alexander, 1987). When put into a simple running model, as the foot comes into contact with the ground, the following eccentric contraction lengthens tendons in series with the muscles eccentrically contracting. The tendon has been suggested to store potential energy (Hof and Van Der Berg, 1986) which assists the concentric contraction. In the running model, the take-off phase (beginning from the extension of the joints), effectively uses less ‘produced’ energy than the movement without the ‘spring’ therefore increasing the efficiency of the movement. It has been shown that less flexible runners are more economical (Jones, 2002) and it was postulated that the stiffer musculotendinous structures associated with less flexible runners reduce the metabolic cost of running by facilitating a greater elastic energy return during the shortening phase of the stretch-shortening cycle. However the results of studies researching relationships between the stretch-shortening cycle and running economy are often conflicting. Caird, McKenzie and Sleivert (1999) put athletes through a 6 week training program and monitored running economy and amongst other variables, the stretch-shortening cycle efficiency. Whereas running economy improved, stretch-shortening cycle efficiency did not and the authors could not attribute a relationship.

In relation to the stretch-shortening cycle, reactive strength can be defined as the ability to quickly change from an eccentric contraction to a concentric contraction (Young, McLean and Ardagna, 1996). Applied to a running model, an athlete’s reactive strength would refer to their ability to quickly push off the ground (extend their lower extremity joints; concentrically contract) from the moment they come into contact with the ground and the lower extremity joints flex to bend the legs (eccentrically contract). The faster the athlete can do this, the greater their reactive strength. Delecluse (1997) has shown that as running speed increases, the increased velocity and stride length result in greater eccentric loads on ground contact, increasing ground contact time and consequently reducing running economy. Most of the current literature regarding reactive strength investigates relationships with sprinters (Young, McLean and Ardagna, 1995; Hennessy and Kilty, 2001) and racket sports or ball games (Young, James and Montgomery, 2002;
Spinks et al., 2007), where maximal speed and agility are crucial elements of performance. Sub maximal running has had virtually no specific attention and as agility and maximal speed have been shown to play only subsidiary roles in middle-distance running performance (Foster and Lucia, 2007) a relationship between reactive strength and running economy can only be speculated. A greater reactive strength will have reduced contact time, consequently increasing running economy and therefore suggesting a relationship. Little and Williams (2005) have shown that as speed increases, reactive strength becomes more important as reducing contact time is crucial. This would seem beneficial to middle-distance runners, as being more economical (through reduced contact times) at higher running velocities would increase performance. In the literature regarding reactive strength, indexes are generally obtained by instructing subjects to perform jumping protocols on force plates, where contact time and flight time can be accurately analysed (Comyns et al. 2007; Flanagan and Harrison, 2007). Previous research have used single-legged rebound and drop jumps, however countermovement squat-jumping would seem more applicable to runners, due to protocol being more representative of the symmetrical mechanics of forward running (Flanagan and Harrison, 2007).
Running Technique Variables

Contact Time

In terms of running technique, contact time is defined as the amount of time spent in contact with the ground on each step. It is well known that ground contact time decreases linearly with increasing running speed (Lahtanen and Komi, 1978) due to a decreased contact time increasing stride frequency, as a limiting factor in stride frequency is the amount of time spent on the ground (Hay, 1993; Coe, 1996). Secondly, there are energy requirements involved in the ‘braking’ forces which runners apply when they come into contact with the ground (Mero, Komi and Gregor, 1992). These braking forces cause a reduction in speed and have been suggested to be the critical point in both sprint running and economical running (Mero, Komi and Gregor, 1992) since, obviously, the longer an athlete is in contact with the ground, the longer the ‘braking’ phase lasts, therefore more velocity is lost and the larger the energy requirement is during the take-off phase, to accelerate the body to the original velocity. This is heavily backed up by the current literature, where studies have measured contact time when athletes have ran over force platforms whilst having previously had their running economy measured (Kyrolainen et al., 2001; Nummela, Kerman and Mikkelsson, 2007), have captured foot-ground contact time during an elite half marathon race and presumed that the fastest were the most economical (Hasegawa et al., 2007) and found results suggesting relationships between contact time (and other biomechanical parameters) and running economy does exist. In addition, decreasing contact time through explosive strength training has been shown to be significantly related to increased running economy (Paavolainen et al., 1999a).
Newton said that every force has an equal and opposite reaction. When in contact with the ground (due to gravity) interactions occur between the body and the ground. Ground reaction force is the term given to the reactive force the ground exerts against the body. It has been suggested that faster maximal running speeds are achieved with greater ground reaction forces (Weyand et al., 2000) rather than higher stride frequencies, however the current literature regarding a relationship between ground reaction force and running economy in distance athletes is generally inconclusive and often conflicting. It has been observed that less economical runners exhibit greater total vertical impulse, indicating wasteful vertical motion (Heise and Martin, 2001). It has been theorized that the heightened metabolic cost of running with a larger ground reaction force is due to the volume of the muscle activated to apply support forces to the ground (Wright and Weyand, 2001). However, Nummela et al. (2007) investigated the relationships between running mechanics, top running speed and economy and found no significant relationship between ground reaction force and running economy. The study was conducted using two tests where the first was used as a means of acquiring running mechanics data, such as ground reaction force, by means of sprint running over force platforms. The second test was used to measure running economy by means of steady state running to set sub maximal paces. An obvious limitation of the Nummela et al. study was that running mechanics variables were not assessed at either the same time or speed as running economy was measured. This may have led to discrepancies in the results due to the change in running technique between sprinting and steady sub maximal state running (Hunter, Marshall and McNair, 2005; Bushnell and Hunter, 2007), specifically the increased ground reaction force that sprint running produces (Mero, Komi and Gregor, 1992). This is evidenced where studies that have measured ground reaction force and running economy in the same test have shown a significant relationship to exist (Heise and Martin, 2001). When distance runners fatigue it has been suggested that impairment to their running economy is a result from an impairment in the force generating capacity of the contractile component (Finni et al., 2003). Although this suggests that the ground reaction force would decrease, contributing to a decrease in running economy, the most
likely cause of a reduction in running economy would be an increase in contact time as a direct result of an impairment to force generating capacity and the associated stretch-reflex (Spurrs, Murphy and Watsford, 2003; Nummela, Keranen and Mikkelsson, 2007).
Running speed is the product of stride frequency (sometimes referred to as stride rate) and stride length (Nummela, Keranen and Mikkelsson), as increasing one or both will result in increased speed (Brown and Ferrigno, 2005). Although this is generally applied in regards to sprint or maximal running the principle can be applied to middle-distance running, where the athlete who maintains the highest average pace will cover the distance quickest. This principle can also be applied to an athlete’s running economy, since being able to maintain faster paces at a reduced metabolic cost will have obvious benefits to a competitive middle-distance athlete.

Stride frequency is measured as the amount of strides taken in a given amount of time or distance. It is generally considered that a quicker stride frequency will result in faster running speed, due to being in regular contact with the ground (Hay, 1993). This seems to make sense as locomotive energy can only be produced when in contact with the ground, therefore as soon as the athlete leaves the ground they will be decelerating. This suggests therefore, that spending as much time in contact with the floor as possible will result in a higher running speed. However, as previously discussed, longer contact times has been shown to reduce running economy (Hasegawa, Yamauchi and Kraemer, 2000; Nummela, Keranen and Mikkelsson, 2007) due to the energy expenditure required on impact with the ground and the braking forces associated (Mero, Komi and Gregor, 1992; Heise and Martin, 2001). Naturally, a reduction in running economy would lead to a reduction in mean running speed through a middle distance race. Therefore it would seem the most economical runner would be in contact with the ground more frequently but only for short periods of time; high stride frequency with short contact time. There may possibly be an optimal combination of the two and future research should be directed at investigating this possibility.

Research has shown that experienced runners will optimise stride frequency to minimise oxygen uptake (Hunter and Smith, 2007). In theory, the higher stride frequency becomes, the larger the strain on the aerobic system. Alternatively, it has been shown that increasing stride frequency increases leg spring stiffness, increasing economy (Farley and
González, 1996). When fatigued, athletes have been shown to increase stride frequency to minimise oxygen consumption (Kyröläinen, Belli and Komi, P, 2001), however fatigued athletes have also been shown to show an increase in stride frequency (Chen, Nosaka and Tu, 2007), presumably due to increased leg spring stiffness and reduced stride length.

Stride length is generally measured as the distance from the initial contact the foot makes with the ground to the following contact with the ground from the same foot. As stride frequency is considered to be relatively constant throughout variations in running pace (Hoffman, 1971; Mero and Komi, 1986; Weyand et al., 2000) it would seem that stride length is a key determinant in running speed and running economy. Manual adjustments to global running technique have been shown to reduce stride length and running economy which suggests a relationship does exist (Dallam et al., 2005). This is in agreement with research done on the effect of muscle damage on running economy, where the resultant muscle damage of downhill running and marathon running was shown to reduced stride length and running economy (Kyröläinen et al. 2000; Braun and Dutto, 2003; Chen, Nosaka and Tu, 2007).

The current literature surrounding a relationship between running mechanics and running economy generally suggests that a relationship exists, but the results of such studies are mostly inconclusive and widely disputed (Foster and Lucia, 2006) with the large majority of the studies merely suggesting that a relationship exists rather than showing a significant relationship exists, due to the lack of evidence. The current study aims to investigate this possible relationship by measuring running mechanics at the same time and velocity as running economy is measured, using well-trained, middle-distance athletes, something that has not been done in the majority of the current literature and possibly a critical aspect to understanding the contributors to running economy (Nummela et al., 2007) and success in middle-distance running.
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 three trials</th>
<th>Subject’s Overall RSI</th>
</tr>
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</tr>
<tr>
<td>1b</td>
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<td></td>
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</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\(^{-1}\))\(^{-1}\). 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\(^{-1}\))\(^{-1}\).
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 (mm 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>Running Velocity (km.hr⁻¹)</th>
<th>Frames per stride</th>
<th>Seconds per stride</th>
<th>Strides per minute (stride frequency)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.1</td>
<td>37.13</td>
<td>0.74</td>
<td>80.79</td>
</tr>
<tr>
<td>17.6</td>
<td>36.07</td>
<td>0.72</td>
<td>83.18</td>
</tr>
<tr>
<td>19.3</td>
<td>35.20</td>
<td>0.70</td>
<td>85.23</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 \( \dot{V}O_2 \) in 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 \( \overline{\text{VO}}_2 \) 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 \( \overline{\text{VO}}_2 \) 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 $\dot{V}O_2$ over the last 30 seconds of each running velocity. The trend line equation and $R^2$ value are only presented for a typical subject (DBI), however, all subjects’ trend line equation and $R^2$ value were calculated.

The subjects’ running economy, expressed as $\dot{V}O_2$ 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 $\dot{V}O_2$ with increasing running velocity, however a significant relationship was not observed.

Table 5. The running economy of the subjects’ when expressed as $\dot{V}O_2$ at 16.1 km.hr$^{-1}$.

<table>
<thead>
<tr>
<th>Subject</th>
<th>$\dot{V}O_2$ (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 \( \dot{V}O_2 \) 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 \( \dot{V}O_2 \) at 16.1 km.hr\(^{-1}\).

![Figure 5](image)

**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.
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 ($r = 0.06$).
CHAPTER V: DISCUSSION
The present study aimed to investigate a possible relationship between running technique and running economy. The main findings were, firstly, running technique was associated with running economy, though more significantly when running economy was expressed as the change in \( \dot{V}O_2 \) with increasing running velocity, opposed to \( \dot{V}O_2 \) at 16.1 km.hr\(^{-1}\). Secondly, that of the running technique parameters, contact time was the most significantly related to running economy.

**Contact Time**

It is well known that ground contact time decreases linearly with increasing running speed (Luhtanen and Komi, 1978) and this was observed in the present study. A greater rate of reduction in ground contact time was significantly correlated \((r=0.95, P<0.01)\) to running economy, when expressed as the change in \( \dot{V}O_2 \) with increasing running velocities. The more economical athletes were shown to decrease their contact time to a greater extent than the other athletes, as the running velocity increased. At 16.1 km.hr\(^{-1}\) or 6 min.mile\(^{-1}\), a positive correlation \((r=0.11)\) between shorter ground contact times and running economy was also observed, although the relationship was not shown to be significant. These findings are in agreement with previous research, where a positive correlation between short contact times and running economy has been documented (Paavolainen, Nummela, and Rusko, 1999; Hasegawa, Yamauchi and Kraemer, 2007; Nummela et al. 2007).

The present study found a significant correlation between ground contact time and running economy, when expressed as the change in \( \dot{V}O_2 \) in relation to increasing running velocity, whilst running on a treadmill. However, Wank, Frick and Schmidtbleicher (1998) found that contact times were significantly shorter during treadmill running that they were for over ground running. It is therefore possible that results observed for ground contact time may have differed had the protocol included over ground running rather than treadmill running. However, this seems unlikely, since the subjects who demonstrated the shorter contact times (and subsequent greater running economy) would be expected to demonstrate shorter contact times over ground running.
A key component to running economy is the ability to store and recover elastic energy from the eccentric contraction, the stretch shortening cycle (Cavanagh and Kram, 1985; Anderson, 1996). Many studies have documented an improvement in running performance and economy through resistance training (Paavolainen et al., 1999) as this training method is thought to improve the stretch-shortening cycle. Jung (2003) suggested this improvement in the stretch shortening cycle caused a significant decrease to ground contact time. In the present study, subjects’ reactive strength index was measured as this is a general indicator of stretch shortening cycle ability (Sewell et al., 2005), and previous studies have documented a significant relationship between reactive strength index and high stretch shortening cycle ability (Paavolainen et al., 1999; Comyns et al., 2007; Flanagan and Harrison, 2007). Correlations between RSI and running economy, expressed as both an increment in $\dot{V}O_2$ and $\dot{\dot{V}}O_2$ at 16.1 km.hr$^{-1}$, were observed ($r=0.26$ and -0.7, respectively). Although a significant relationship could not be attributed, correlations were present and the present study is therefore in support of the previous research documenting firstly, a relationship between a greater stretch shortening ability and a greater running economy and secondly, the theory that the increase in running economy observed with increase in the stretch shortening cycle is due to the consequent reduction in ground contact times.

A recent study by Hasegawa, Yamauchi and Kraemer (2007) analysed the foot strike patterns of runners during an elite level half marathon and found that foot strike patterns are related to running speed. They found that the faster runners tended to have a higher frequency of inversion at foot contact, stipulating that this could contribute to a higher running economy. In addition, Ardigo et al. (1995) found that contact time was greater in rear foot strike runners and attributed that this type of foot strike required a longer time of muscle activation to accelerate their body than mid- and front-foot strike runners. Although foot strike variables were not measured in the present study, foot striking patterns may partly explain the variation in contact time and subsequent variation running economy observed across the subjects.
Previous studies have shown that the energetic cost of running is significantly related to the stiffness of the propulsive leg (McMahon, Valiant and Frederick, 1987; Zamparo et al., 1992; Dalleau et al., 1998). These studies observed that greater leg stiffness decreases ground contact time, which is presumably the explanation for leg stiffness’ relationship with running economy. Subject leg stiffness was not measured during the present study but the previous research suggests that leg stiffness may explain the variation in contact times and consequent variation in running economy observed.

Strength training has been heavily linked to improving running economy (Aura and Komi, 1986; Kyrolainen, Komi and Kim, 1991; Paavolainen et al. 1999). Endurance athletes through 9 weeks of sport specific explosive strength training concomitantly with their endurance training. Subjects’ running economy was improved and the ground contact time was significantly decreased, whereas no changes were observed in ground reaction forces or maximal forces of the trained muscle, providing evidence that explosive strength training decreased contact time which subsequently increased running economy. This suggests that in the present study, the more economical athletes shorter contact time may be explained through greater explosive strength. Furthermore, it has been suggested (Aura and Komi, 1986; Kyrolainen, Komi and Kim, 1991) that explosive strength develops certain aspects of the nervous system that plays an important role in regulating muscle stiffness and utilisation of the muscle elasticity during stretch shortening cycle exercises. Both these aspects have been suggested to be beneficial to lower contact times.
Stride Characteristics

Previous research has shown that athletes tend to subconsciously choose their own stride length that reduces the metabolic cost of running at that particular speed (Cavanagh and Williams, 1982) and that there is significant relationship between stride length and running economy. These findings were reflected in the present study, where subjects showed a large variation in stride length at all velocities (see Figure X) and no significant correlation between stride length and running economy was observed.

Deviations from a runner’s pre-selected, optimal stride length have been significantly related to an increase in the oxygen cost of running at fixed velocities, such that increasing and decreasing stride length both increased the oxygen cost of running. Interestingly, increasing stride length was shown to be more detrimental to running economy (Högberg, 1952; Cavanagh and Williams, 1982).

In the present study, stride frequency was shown to be correlated to ground contact time (r=0.76), which was expected as stride frequency is a compound parameter, depending on both contact and aerial time (Morin et al., 2007). Hunter and Smith (2007) found that a decrease in stride frequency of around 1-2% was related to a 3% increase in oxygen uptake during an hour run and suggested that fatigue induced reductions in stride frequency lead to a decrease in running economy. This reduction in running economy is presumably due to the increase in ground contact times associated with a decrease in stride frequency. In addition, Farley and Gonzalez (1996) found that when humans increase their stride frequency at a given speed, their leg stiffness is increased. Farley and Gonzalez also observed that leg stiffness can be changed to accommodate differing stride frequencies. It would seem that runners who can increase their leg stiffness to the greatest extent can increase their stride frequency to the greatest extent, benefiting running economy through a lowered energy cost at that speed due to the decreased ground contact times. Similarly, when stiffness is decreased, stride frequency is decreased (Farley and Gonzalez, 1996). It is thought that decreased leg stiffness creates a more compliant running style which will increase contact times and create larger, wasteful ground
reaction forces (Heise and Martin, 2001). During prolonged, fixed speed running, stiffness has been shown to gradually decrease (Braun and Dutto, 2007), presumably due to fatigue. As Fatigue in running is a multi-dimensional response, which influences physiological and biomechanical characteristics to change away from baseline conditions (McClaren et al. 1989), internal changes with fatigue may affect stride characteristics and contribute to the degradation of running economy. Joints and tendons are thought to exhibit decreased stiffness after fatiguing exercise (Kuitunen et al., 2002; Kubo et al., 2001). The repeated eccentric muscle activations which occur in running result in a reduced capacity for muscle stretch and some delay in the stretch shortening cycle which may lead to changes of stride mechanics involving greater knee flexion (Noakes, 2000). Hunter and Smith (2007) theorised that maintaining stiffness of the muscle tendon complex would require the runners to recruit additional fast twitch muscle fibres compared to the initial state. This would increase the metabolic cost of the movement (McArdle, Katch and Katch, 2006) and could therefore provide and explanation for why stride frequency and stiffness is related to running economy. Therefore, the ability to increase stride frequency with increasing running speed would seem beneficial to running economy, since reducing stride frequency has been shown to be detrimental. Although the present study could not attribute a significant relationship between stride frequency and running economy, a relatively strong, positive correlation was observed (r=0.62). Hunter and Smith (2007) suggested that stride characteristics become more variable due to the demands of increasing frequency stages and requiring breathing through the oxygen uptake mask and tube, which could well make the detection of significant relationships more difficult.

Running technique variables were shown to be stronger correlated to running economy when expressed as change in $\dot{V}O_2$ with increasing running velocity, as opposed to running economy expressed as $\dot{V}O_2$ at 16.1 km.hr$^{-1}$. It has been suggested that at 16.1 km.hr$^{-1}$, well-trained, middle-distance athletes (similar to the present study’s subjects), running economy represented as $\dot{V}O_2$ is weakly correlated to running performance, possibly due to the majority of their training being performed at this pace (Martin and Coe, 1997; Noakes, 2005). The present results suggest that running technique is more
strongly correlated to running economy when the latter is physiologically stressed. It has been suggested (Kyrolainen, Pullinen and Candau, 2000) that the first changes the body initiates to reduced the metabolic cost of an activity (that is, running) are physiological, such as raising core temperature and increasing minute ventilation. When these variables can no longer be adjusted, changes to biomechanical variables occur. Well-trained middle-distance athletes typically train regularly at 16.1 km.hr⁻¹, at this running velocity, the physiological alterations are not at their threshold, and as a result, technique variables appear to have little correlation with running economy. However when running economy is expressed as the change $\dot{V}O_2$ with increasing velocities reaching almost 20 km.hr⁻¹, the physiological variables are at their respective thresholds and so, limitations in the alterations to running technique variables become the determining factor in the metabolic cost of exercise.

The results of the present study are in agreement with that of previous research that firstly, optimal stride length is self-determined by the individual and no clear relationships between it and running economy seem to exist. Secondly, stride frequency would appear to be positively correlated to running economy, presumably due to the increases in leg stiffness which create a less compliant running style with associated increased propulsive leg stiffness, and consequent reduced ground contact time, leading to a reduced metabolic cost of running.
Practical Implications

A major implication with the present study was the lack of control over the subjects’ training prior to the study. As a result, subjects may have been assessed whilst at differing levels of their individual fitness, which could affect running economy values. In addition, the training subjects were performing immediately prior to exercise protocol was not controlled. As a result, there may have been a variation in fatigue between the subjects upon testing. Fatigue in running is a multi-dimensional response, which influences physiological and biomechanical characteristics to change away from baseline conditions (McClaren et al. 1989), thus affecting both running economy and technique.

Standardisation of the subjects’ training over the weeks and months leading up to the study may have controlled these possible implications. Furthermore, subjects’ strength training was not controlled. As a result, subjects may have been tested whilst at differing levels of their overall strength, further affecting running economy and technique.

All running during the present study was performed on a treadmill inclined to a 1% gradient, as this has been suggested to mimic the oxygen cost of outdoors running (Jones and Doust, 1996). The present study assumed that running technique would not be significantly different between outdoor track running and treadmill running on a 1% gradient. It has also been assumed that running with an oxygen uptake mask and tube would not effective running economy or technique, as Hunter as Smith (2007) suggested it may do.

Conclusions & Future Directions

This study has provided evidence that running technique is associated to running economy, most significantly through the parameter, ground contact time. In the present study this was the only parameter that was significantly (P<0.05) correlated to running economy. It is thought that a greater explosive strength contributes to increased leg stiffness during the propulsive phase of running. This increased leg stiffness increases stride frequency which causes a reduction to ground contact time. A greater ability to
utilise the elastic energy stored during the stretch shortening cycle at the musculotendinous unit associated with running also decreases contact time.

In light of the findings of the present study, future research should be directed toward identifying methods for decreasing contact time to maximise running economy and subsequent middle-distance performance. Strength training has been suggested to decrease ground contact time through its effect on the nervous system’s role on muscle stiffness and stretch-shortening capabilities. Therefore future research should aim to identify optimal strength training programs that would most efficiently improve these aspects.


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


APPENDICES
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.