The Acute Effects of Intense Interval Training on Running Mechanics

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June 1998

A Thesis Submitted to the Faculty of Graduate Studies and Research in Partial Fulfillment of the Requirements for the Degree of Master of Arts (M.A.)

0-612-43856-2

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Abstract

The purposes of this study were to determine 1) how running kinematics varied across two different speeds (200 and 268m/min), 2) to what degree intense interval training sessions affected running mechanics and 3) whether these changes correlated to changes in running economy (RE). Eleven highly trained male endurance athletes (average $VO_2max = 72.5 \pm 4.3$ ml/kg/min) performed three intense interval running workouts of 10 x 400m at an average running velocity of 357.9 ± 9.0 m/min, with a minimum of 4 days between runs. Recovery duration between trials was randomly assigned at 60s, 120s, and 180s. The following biomechanical variables were used to assess running kinematics during the last 3 minutes prior to and following each workout at speeds of 200 and 268m/min: maximum knee flexion in support (KFLEX), minimum knee velocity during stance (KVEL), maximum plantar flexion angle at toe-off (PFLEX), shank angle at heel strike (SANG), mean trunk angle during stride cycle (TANG), mean vertical oscillation of center of mass (VOSC), and stride cycle length (SL). Results of this study affirmed our hypothesis that speed significantly impacts on some kinematic variables (KVEL,SANG, SL), and to a degree has shown that pre and post test and recovery conditions creating a fatigued state altered 2 of the kinematic variables (KVEL and VOSC). However, none of the other kinematic variables measured were altered by speed or fatigue in any substantial way, nor were there any clear correlations between changes in running economy and mechanics. Whether the significant kinematic changes that occurred reflect adaptations to fatigue, rather than a failure to compensate for it , is not clear. The interrelationship between metabolic and biomechanical markers of training and performance appears to be complex and somewhat individualistic.

Résumé

Cette étude visait à déterminer 1) l'effet de la vitesse (200 et 268 m/mn) sur la cinématique de la course; 2) dans quelle mesure une séance intensive d'entraînement par intermittence affecte la mécanique de la course; 3) s'il existe une corrélation entre ces variations et les variations de l'économie de la course (EC). Onze coureurs d'endurance ayant suivi un entraînement poussé (VO_2max moyen = 72.5 ± 4.3 ml/kg/mn) ont exécuté trois séances intensives d'entraînement par intermittence (10 x 400 m à une vitesse moyenne de 357.9 ± 9.0 m/mn) entrecoupées d'au moins 4 jours de repos. Le temps de repos entre chaque segment parcouru durant les séances (60 s, 120 s et 180 s) a été déterminé de façon aléatoire. Les variables biomécaniques suivantes ont été utilisées pour évaluer la cinématique de la course durant les trois dernières minutes du test effectué avant et après chaque séance d'entraînement, à des vitesses de 200 et de 268 m/mn : flexion maximale du genou en phase d'appui (KFLEX), vitesse minimale du genou en appui (KVEL), angle maximal de flexion plantaire au moment où le pied quitte le sol à la fin de la foulée (PFLEX), angle du segment inférieur de la jambe au contact du talon (SANG), angle moyen du tronc durant la foulée (TANG), oscillation verticale moyenne du centre de gravité (VOSC) et longueur de la foulée (LF). Les résultats de cette étude ont confirmé notre hypothèse et démontré que la vitesse a un effet considérable sur certaines variables cinématiques (KVEL, SANG, LF); ils ont aussi démontré jusqu'à un certain point que le prétest et le post-test et les conditions de récupération créent un état de fatigue qui modifie 2 des variables cinématiques (KVEL et VOSC). Toutefois, aucune autre variable cinématique mesurée n'a été modifiée de façon notable par la vitesse ou la fatigue et il n'existe aucune corrélation claire entre les variations de l'économie de la course et de la mécanique. Il n'a pas été possible de déterminer si les changements cinématiques importants intervenus reflètent l'adaptation à la fatigue ou au contraire l'incapacité de l'athlète à pallier celle-ci. La relation réciproque qui existe entre les marqueurs métaboliques et

biomécaniques de l'entraînement et de la performance semble complexe et varie selon les individus.

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List of Abbreviations

Abbreviation	Term
RE (ml/kg/min)	Running economy
VO_2max (ml/kg/min)	Maximal oxygen uptake
$VO_2submax$ (ml/kg/min)	Submaximal oxygen uptake
HR (bpm)	Heart rate
RER	Respiratory exchange ratio
SL (m)	Stride length
SR	Stride rate
KFLEX (degs)	Maximum knee flexion in support
KVEL (cm/s)	Minimum knee velocity during stance
PFLEX (degs)	Maximum plantar flexion angle at toe-off
SANG (degs)	Shank angle at heel strike
TANG (degs)	Mean trunk angle during stride cycle
VOSC (cm)	Mean vertical oscillation of center of mass

Acknowledgements

The author wishes to thank Dr. D. Pearsall, Dept. of Physical Education, McGill University, for his patient supervisory role of this thesis, Hamid Bateni for his work on the digitization of the data, Marguerite Roy, Applied Cognitive Science Research Group, McGill University, for her expert advice on the statistical analysis, and Pierre Popovic, Mirotech Microsystems, for his invaluable help with the graphics and design layout of this paper. The author also wishes to thank Dr. D. Montgomery and Gerry Zavorsky for their cooperation with the filming of the subjects.

1. Introduction

Biomechanical variables are believed to play an important role in determining external energy demand. It has been postulated that a reduction in external energy expended will result in an improvement in running economy (Bailey et al. 1991). While most of the research literature has investigated the relationship between a number of physiological factors and running, few studies provide insight into how the various descriptors of running mechanics affect economy. At present, it is not possible to distinguish whether mechanical variables describing the running pattern of an uneconomical runner contribute to making the runner uneconomical, or whether the pattern reflects the means by which the individual has optimized his or her own anatomical and physiological features.

This paper will review the research literature that has studied the relevant physiological, environmental, structural, and mechanical factors that are associated with a lower aerobic demand in running. External energy (factors that a runner has limited or no control over) includes age, segmental mass distribution, stride length, and other biomechanical variables. Internal energy includes ventilation, temperature, $V0_2max$, training status, fatigue and mood (Bailey et al. 1991). The focus on running economy (defined as a steady-state $V0_2$ for a given running velocity) is due to the fact that it has been shown to account for a significant proportion of variation in middle and long distance running performance among runners of roughly comparable $V0_2max$. In fact, while the relationship between $V0_2max$ and distance running performance was $r = -0.12$ ($p = 0.35$), the relationship between steady-state $V0_2$ at 241, 268, and 295m/min. and

10km time were $r = 0.83$ ($p< 0.01$). Approximately 65.4% of the variation observed in race performance time on a 10km run could be attributed to running economy (Conley et al. 1980). Similarly, Morgan et al. (1989) found that among well-trained subjects homogeneous in $V0_2$max, a strong relationship exists between 10km run time and velocity at $V0_2$max that appears to be mediated to a large degree by running economy (RE).

It is the intent of this paper to clarify the biomechanical considerations relevant to RE, and to determine whether intense interval training sessions can significantly alter running mechanics, and hence impact on RE. In assessing the physiological factors that best estimated RE in average to good runners, Pate et al. (1992) found that the variables ventilation (VE), heart rate (HR), $V0_2$max (ml/kg/min) and bodyweight were the better determinants. However, it is unclear as to whether or not the same set of variables will best predict RE in elite runners. Also, Daniels et. al. (1984) found that intraindividual running economy in trained subjects varied by as much as 11% when running speed, learning, footwear and test equipment were controlled. In contrast, Morgan et al. (1988) found that stable economy values could be obtained in trained runners if, in addition to the above, training activity and time of day were controlled.

Factors such as age, gender, training and body mass also affect the energy cost of running. Bourdin et al. (1993) compared the energy cost of running (Cr) - expressed as $ml0_2$/kg/min - of young boys (avg. age 14.2), young girls (avg. age 12.2), and male and female middle distance runners (avg. age 23.7 and 23.9). For each group, the results showed that body mass and height were negatively and significantly correlated to Cr. In addition, for a given body mass, the female middle distance runners showed a significantly lower Cr than any other group. In contrast to this gender difference, Bransford and Howley (1977) found men at the same level of training had significantly lower Cr than the women, and noted that elite male runners were capable of greater economy than women. However, this study did not take into account the influence of gender on body dimensions. In fact, most evidence suggests that aerobic demand of submaximal running is not significantly different between males and females when expressed relative to total body mass (Maughan and Leiper, 1983; Daniels, 1985;1977).

Another obviously important factor in determining RE is training status. Unfortunately there have been few attempts to quantify the relative contributions of physiological and biomechanical adaptations towards improved performance (Anderson, 1996). Several studies have indicated that RE is improved by training. Patton and Vogel (1977) showed that a 6 month conditioning program consisting of long distance running at moderate intensities (2 and 4 mile runs at 8 to 9 minute per mile paces) significantly improved economy in untrained and trained military personnel. Short term longitudinal studies (6 months) have demonstrated that interval training, or a combination of interval and long distance training improves running economy (Conley, 1981). Similarly, Sjodin et. al. (1982) found that by supplementing regular training with 1 weekly 20 minute run at high intensity improved RE in middle and long distance runners (Sjodin et al. 1982). In contrast, Overend et al. (1992) found that neither low or high power output interval training on cycle ergometers offered any advantage over continuous training at the same average power output in altering the aerobic parameters of $V0_2max$, ventilation threshold, effective time constant for 0_2 uptake kinetics, and work efficiency. However, Gorostiaga et al. (1991) found that interval training produced higher increases in $V0_2max$ and in maximal exercise capacity than continuous cycle training, whereas continuous training was more effective at increasing oxidative capacity and delaying the accumulation of blood lactate levels during continuous exercise.

Daniels et al. (1978) investigated the relationship between VO_2max and running performance in 12 untrained individuals and 15 well-trained runners, after 4 and 8 weeks of controlled long distance and interval training. In the untrained group, VO_2max increased during the first 4 weeks of training only, while running performances improved throughout the training period. In the well-trained runners, neither VO_2max or $VO_2submax$ changed, but running performance improved. These results indicate that not all of the improvement in running performance is attributable to changes in VO_2max, nor do changes in RE explain performance improvement in well-trained runners. In fact, Houmard et al. (1990) found that for well-trained runners, many of their endurance training adaptations and racing performance times were maintained in spite of 3 weeks of reduced training. The consensus of data indicates that trained subjects are more economical than untrained or less trained counterparts (Bransford and Howley, 1977; Daniels, 1985; Pollock et al. 1980), yet to what extent physiological versus mechanical factors influence this RE remains unclear.

1.1 Significance of the study

It is believed that running performance is mediated to a large degree by RE (Morgan et al. 1989). Factors such as fatigue have been shown to affect RE (Cavanagh, et al. 1985; Brueckner et al. 1991; and Nicol et al. 1991), while other studies have shown no changes in RE after a prolonged exercise bout (Martin et al. 1987; Morgan et al. 1988; 1990). Williams and Cavanagh (1987) indicated that the mechanics of running has an influence on these metabolic costs, and a substantial portion of the variance in VO_2submax could be explained by biomechanical variables ($R^2 = 0.54$).

It is not clear as to what the effects of intense, long duration runs or overtraining has on RE, and to what degree these changes are mediated by biomechanical alterations in the running gait pattern. Related to this question is the possibility that overtraining ultimately impacts on performance creating higher aerobic demand and changes in running mechanics. To what extent, and for how long these changes remain is still to be determined. Therefore, there is a need to identify the interrelationships among metabolic, biomechanical and psychological markers of training and performance, in particular, the acute effects of intense interval training on RE and running mechanics.

1.2 Purpose of the study

This study addresses the issue of high intensity interval training and its immediate effect on running economy and running mechanics. The purpose of this research project is two-fold:

1) the physiological component conducted by Zavorsky et al. (1998) examined the following hypotheses:

   1) The post-workout RE will be significantly higher than the pre-workout RE.

   2) The post-workout RE will be significantly different among the three rest-recovery conditions (60, 120, and 180 seconds).

   3) There will be significant interaction among rest-recovery conditions and speed (200 and 268m/min) for RE.

   4) There will be significant interaction among speed and test-time (pre and post-workout) for RE.

   5) There will be significant interaction between rest-recovery and test-time for RE.

2) the biomechanical component of this study investigates the following hypotheses:

   i) There will be significant biomechanical changes in running pattern pre and post interval training sessions (pre and post-workout).

   ii) Running speed (200 and 268m/min) will produce significant biomechanical differences.

   iii) Post-workout running mechanics will be significantly different among the recovery conditions (60,120, and 180 seconds).

A fourth component of this study is to interpret whether any observed changes in running economy are related to changes in running mechanics due to the intense interval training sessions.

1.3 Operational Definitions

1) Pre-workout RE: Running economy measured before an interval workout of 10x400m.

2) Post-workout RE: Running economy measured after an interval workout of 10x400m.

3) Rest-recovery: The amount of rest taken between each trial of 400m in the interval workout.

4) VO_2max: The maximal aerobic speed of an individual as determined by a VO_2max test.

5) 10x400m: The interval workout which consists of running ten, 400m repeats.

6) Oxygen cost: Words that are used interchangeably with "oxygen consumption", "aerobic or oxygen demand", "$VO_2submax$", and "RE".

1.4 Delimitation

The subjects are 12 elite male MD (800-1500m) or LD (> 5000m) runners between 18 and 35 years of age.

1.5 Limitation

The filming speed and digitizing procedure used in this study may differ from other studies due to different high speed cameras and digitizing equipment.

2. Review of literature

Biomechanical considerations affecting running economy

Running economy (RE) has been associated with various physical and mechanical descriptors. The following summary will outline factors presumed to influence RE, and to what degree these factors can account for some of the interindividual variability commonly observed.

2.1 Structural factors associated with running economy

There are a variety of anthropometric dimensions that can alter the biomechanical effectiveness with which muscular activity is converted into forward translocation, and therefore influence the energy cost of running. The following physical factors have been shown to impact on RE.

2.1.1 Body mass

Even though RE is usually normalized to body mass, it may still account for some of the interindividual variability in economy. Based on animal studies, Taylor (1994) contends that the cost of running decreases with body size on a mass-specific basis. These findings are supported by Davies (1980) who observed lower aerobic demands for loaded versus unloaded (increase of 5% bodyweight on trunk) conditions running at higher speeds (14 to 16 km/hr) . Similarly, Bergh et al. (1991) showed that endurance trained men and women's VO_2 at a given velocity did not increase in proportion to body mass; instead the oxygen uptake per kilogram decreased with increased mass. Apparently differences in RE which had traditionally been attributed to age and gender may be related more to factors of height and body mass. Daniels et al. (1977), in comparing 10 highly trained male and female runners, also concluded that the better absolute performance of the men was a function of size differences. From a study of 14 elite female distance runners, Williams et al. (1987) found a modest inverse relationship ($r = -0.52$) between body mass and economy, indicating that heavier than average runners exhibited better economy than lighter runners. Bale et al. (1986) found that within a group of 60 male distance runners, the elite and good runners had significantly higher ponderal indices (ratio of body weight divided by height), and were less endomorphic than the average runners. The results of Bourdin et al. (1993) supported the previous findings in that the energy cost of running(Cr) was significantly correlated to height and body mass. In fact, Williams and Cavanagh (1986) noted that for elite male runners, anthropometric variables such as leg length, pelvic width and foot length were more highly correlated to RE than those describing running mechanics.

2.1.2 Body and segment mass distribution

Upon further examination of the relationship between body mass and running economy, Cavanagh and Kram (1985) proposed that individual differences in distribution of mass among limb segments are important factors. Similar findings support this hypothesis. For example, Myers and Steudel (1985) studied leg morphology and the effects of the distribution of added mass. The results indicated that all limb loadings resulted in greater increases in energy cost than when the same mass was carried at the waist. It was hypothesized that a smaller individual possesses a relatively greater amount of body mass in the extremities, and would therefore have to perform a relatively greater amount of work moving his/her body segments during running. Indirect support for this hypothesis comes from various loading studies (Martin, 1985; Keren et al. 1981; Jones et al. 1984). Burke and Brush (1979) found smaller bone diameter and shorter upper leg length in proportion to lower leg length in successful teenage female runners, supporting the notion that the closer the center of gravity of the whole leg to the hip joint, the smaller the moment of inertia during recovery and hence lower kinetic energy to accelerate and decelerate the limbs. Williams and Cavanagh (1986) found a negative correlation between foot length and running economy in elite male runners. However, Taylor (1994) cites findings that gazelles, goats and cheetahs use nearly the same amount of energy to run over a wide range of speeds despite a 30-fold difference in moments of inertia of their limbs, and their energy cost is nearly identical to that predicted by their body mass, rather than body and segmental mass distribution. Unfortunately, these findings may not be directly applicable to humans due to the differences in running gait patterns. Although segmental mass distribution may affect running economy to a small degree, there is no effective practical means by which a runner can alter this to his/her advantage, and will not be considered an important variable in this study.

2.13 Flexibility/joint range of motion

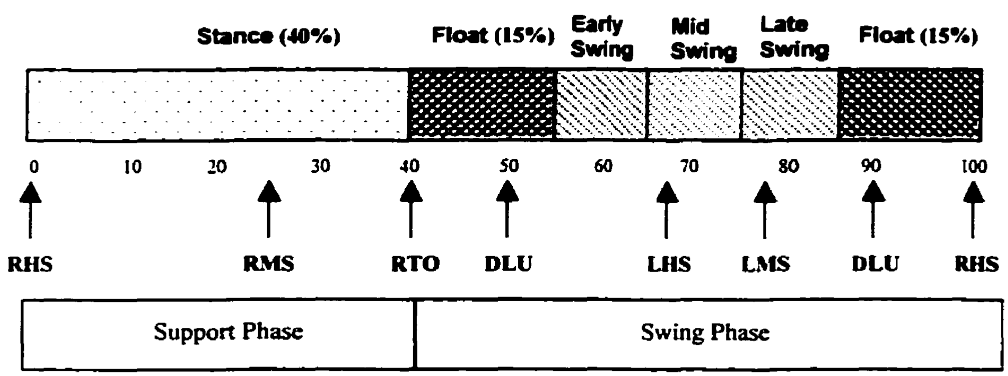
It has been theorized that flexibility declines could result in a modified gait pattern that is less economical, but in fact, Gleim et al. (1990) found that "nonpathological musculoskeletal tightness" was related to lower aerobic demand during walking and jogging perhaps due to the enhanced elastic energy contributions or less need for neutralization of unproductive movements by active musculature in less flexible individuals. It has been proposed that improvements in the economy of running mechanics is related to the more effective storage and release of elastic energy (Alexander, 1991; Taylor, 1994). The degree of flexibility that is optimal in achieving this effective release of elastic energy remains to be determined. It is important to maintain a flexible gastrocsoleus complex as tightness will decrease dorsiflexion and alter the way the body can move over the center of gravity of the hindfoot during the stance phase resulting in increased energy costs (Adelaar, 1986). Training status would also play an important role in neutralizing unproductive movements as running mechanics improve, which may indirectly be influenced by a minimum range of motion in the joints. Further studies are needed to directly relate range of motion, elastic energy, and RE.

2.2 Kinematic descriptors of running

In discussing the biomechanics of running and its relationship to running economy, one must define what is meant by a running gait pattern, in particular, a running stride cycle. A pace faster than 201m/min is considered running (Adelaar, 1986). The running cycle is divided into a stance phase (40%) and a swing phase (60%). A stride is the distance measured from heel strike (foot contact) to heel strike of the same leg, whereas a step is defined as the distance from right heel strike to left heel strike or vice versa. Within the swing phase, there are two "float" phases occurring just after right and left toe-off, constituting approximately half of the swing phase time (Adelaar, 1986). Refer to Figure 1.

FIGURE 1

RUNNING STRIDE CYCLE



RHS: right heel strike
RMS: right mid stance
RTO: right toe off
DLU: double limb unsupported

Adelaar.R. 1986
Reber. L. et al. 1993
(adapted)

2.21 Gait pattern/stride length/stride frequency

The gait element which has been studied extensively is the balance between stride length and frequency. The basic assumption appears to be that strides which are too long will require greater aerobic demands and result in excessive vertical oscillation of the center of mass, produce a foot strike that requires large braking forces and require joint ranges of motion which invoke internal friction. Conversely, strides that are too short would increase internal work through increased frequency of reciprocal movements (Anderson, 1996).

Some performance related data indicate that " more skilled " runners tend to have longer strides at any given velocity than " less skilled " runners (Dillman, 1975), whereas Cavanagh et al. (1977) found that elite distance runners took shorter absolute and relative strides than good distance runners. Relationships between stride length and various anthropometric dimensions have been low to moderate, but do show a tendency for individuals who are taller, heavier, longer legged and heavier legged, and have limbs with greater moments of inertia to take longer strides (Williams and Cavanagh, 1987). Holt et al. (1990) found that stride length/rate optimization is directly associated with anthropometric and inertial characteristics of the legs, that is, "motor control parameters emerge from the physical attributes of the system." Cavanagh and Williams (1982) found that a comparison of leg length (LL%) versus optimal stride length showed a surprising negative correlation of -0.44. However, extreme data from 2 subjects greatly influenced these results, and when removed they found a very low correlation of 0.09. Due to individual variability, it appears that in general it is not possible to predict optimal stride length on the basis of leg length.

Kaneko et al. (1987) observed U-shaped relationships between economy and stride rates (SR), and between economy and total body mechanical power. At low stride rates, external mechanical power (computed from kinetic and potential energy changes of the body center of mass) was high. At high stride rates, the mechanical power associated with moving limbs was at its highest level. It was speculated that these extreme conditions require a greater reliance on less economical fast twitch fibres than the more intermediate stride/length frequency combinations. It is likely that individuals, particularly elite runners, use a combination of SL and SR that minimizes their metabolic costs of running. From Table 1, it can be seen that correlations between stride length (SL) and various anthropometric measures is generally low.

Table 1: Correlation between SL and various anthropometric measures

AUTHORS	VELOCITY	n SUBJECTS	SL vs BODY MASS r	SL vs LL r
Svedenhag & Sjodin (1994)*	4.6 m/s. & 5 m/s.	17 elite	"Low"+ve	"Low" -ve
Cavanagh & Williams (1982)	3.83 m/s	10	—	0.09
Cavanagh et al. (1977)	4.97 m/s	14 elite 8 good	—	0.67 -0.10
Eliott & Blanksby (1979)	4.5 m/s	10	—	0.68
Williams et al. (1987)	5.33 m/s	14 elite females	—	+ve

* used body-mass-modified RE (ml/0.75kg/min)

2.22 Vertical oscillation of body center of mass (VOSC)

Vertical oscillation of the center of mass has been studied as a biomechanical variable that may affect running economy. Intuitively, increased oscillation is adversely related to economy, and in fact Cavanagh et al. (1977) found that elite distance runners had slightly smaller vertical amplitude of center of mass than good distance runners, and a consistent trend towards lower oxygen cost

(Williams and Cavanagh, 1987). However, there is evidence that many individuals can run economically despite having a relatively high vertical oscillation (Williams,1990). Perhaps this is due to the fact that no one parameter of motion will account for a major portion of the total energy costs. Also a higher vertical oscillation may reduce energy costs associated with swing phase by increasing the time to get the trail leg through to the next foot strike.

2.23 Other relevant kinematic and kinetic descriptors

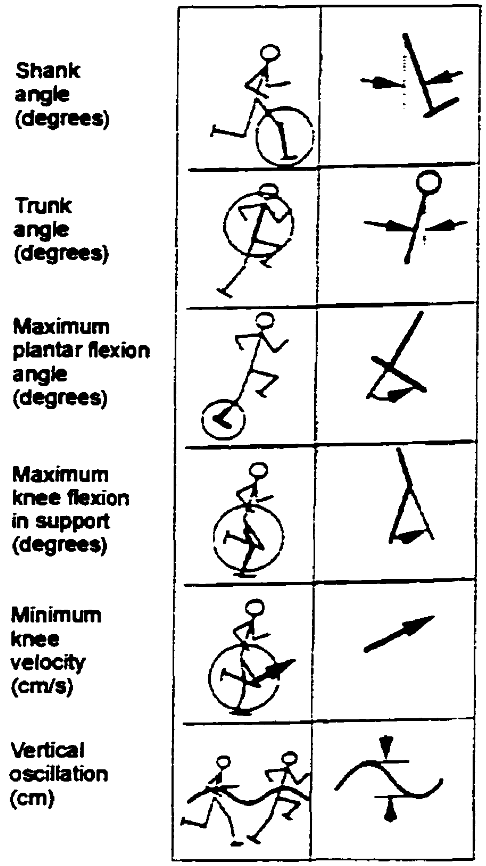
Williams and Cavanagh (1987) found that the high running economy group showed a significantly greater angle of the shank with the vertical at heelstrike than the low economy group (SANG), while Cavanagh et al. (1977) showed that elite runners exhibited more acute knee angles during swing, and that good runners plantar flexed an average of 10 degrees more during toe-off than elite runners (PFLEX).

Williams and Cavanagh (1987) also found that the high running economy group tended to have greater knee flexion during support (KFLEXS) and greater forward trunk lean from vertical (TANG) during the running cycle than the low economy group. They also found that the high economy group demonstrated a lower minimum velocity of the knee during foot contact (KVEL) than the low economy group.

A final kinematic gait element that has been studied relative to RE is arm movement or wrist excursion (WEXC). Studies have shown that there is a trend for more economical runners to exhibit less arm movement and amplitude as measured by wrist excursion during the stride (Williams and Cavanagh, 1987;

Anderson and Tseh, 1994). Refer to Table 2 for the selected kinematic measures used in this study that replicate those used by Williams and Cavanagh (1987).

Table 2 Kinematic variables used in this study



Adapted from Williams & Cavanagh, 1987.

Two common kinetic descriptors of running mechanics analyses is the vertical ground reaction force measured at heel strike (VGRF), and foot pressure patterns. High ground reaction forces are associated with increased energy costs, due to the need for more intense muscular contributions to control segmental movements and stabilize the body during the support phase (Williams, 1990). Foot pressure analyses involve the measurement of the center of pressure patterns, together with the pressure distribution under each foot during running, allowing researchers to find anomalies in loading patterns (Cavanagh et al. 1985). These two variables will be further discussed in section 2.4 Running kinetics and economy. To summarize, Table 3 below lists the biomechanical factors related to better economy in runners.

Table 3. Biomechanical Factors Related to Improved Running Economy
Average or slightly smaller than average height for men and slightly greater than average height for women
High ponderal index (ratio of body weight divided by height)
Low percentage body fat
Leg segment mass distribution closer to hip joint
Narrow pelvis
Low vertical oscillation of body center of mass
Freely chosen stride length over substantial training time
Slightly greater forward trunk lean
More acute knee angles during swing
Less range of motion but greater angular velocity of plantar flexion during toe-off
Arm motion that is not excessive
Low peak ground reaction forces
Faster rotation of shoulders in the transverse plane
Effective utilization of stored elastic energy
Running surface of intermediate compliance

2.3 Running kinematics and economy

Research has shown that training bouts and long distance running can and do affect running economy and kinematics, yet to what degree and for how long do these changes remain, is still to be determined. Kinematic analysis measures the linear and angular displacement, velocity, and acceleration of a body without regard to the forces causing the motion. This study addresses the issue of high intensity interval training and its immediate effect on RE and running mechanics. This information may assist in developing training techniques to ensure optimal running performances.

Several linear and angular kinematic measures of the body while running have been related to RE. Table 4 provides a summary of the kinematic variables shown to have a correlation with RE. For most studies, only trends in relationships were indicated as opposed to stated r values.

Table 4: Kinematic variables shown to have a correlation with RE.

Kinematic variable	**Correlation trends**					
	Williams & Cavanagh (1987)	Cavanagh et al. (1977)	Cavanagh & Williams (1982)	Dillman (1975)	Morgan et al. (1988)	Willams et al. (1987)
Vertical oscillation of CM	-ve	-ve			-ve*	-ve
Trunk lean	+ve*					
Shank angle at foot strike	+ve*					
Max. planter flexion angle	-ve*	-ve				
Min. knee velocity	-ve					
Max. knee flexion and support	+ve trend					
Stride length		-ve	+ 0.41	+ve	-ve*	+ve
Wrist excursion	-ve trend					

* significant differences between high and low economy groups were found ($p<.05$)

Stride length (SL) is a variable that has been shown to have a direct effect on running economy. Cavanagh and Williams (1982) found that the freely chosen stride lengths of recreational runners minimized O_2 uptake at a controlled speed.

During unrestricted running, the main increases in VO_2 were 2.6 and 3.4 ml/kg/min at the short and long stride length extremes, showing a curvilinear relationship between stride length and economy.

Kaneko et al. (1987) further illustrated this link by quantifying the mechanical power output for several stride frequency/length conditions. Their results showed the expected curvilinear response between economy and stride frequency, as well as between economy and mechanical power, though to a somewhat lesser extent. It was postulated that this economy response may be due to the recruitment of less economical fast twitch fibres at the extreme ranges.

Investigation of the variations in stride length inherent in novice male runners found no significant effect on RE during an initial 7 week training program, when compared to the controlled stride length group, yet the relative submax VO_2 values decreased significantly in both groups (Bailey and Messier, 1991). In contrast, Dillman (1975) found that more experienced runners possess greater relative stride lengths than less experienced, perhaps due to the fact that the mechanism for increasing speed appears to be one that maintains stride frequency, necessitating an increase in stride length (Cavanagh and Kram, 1990).

In order to account for the constraints anthropometric variables may place on stride length, Svedenhag and Sjodin (1994) investigated body-mass-modified RE and step lengths at different velocities in elite middle and long distance runners. Step lengths at 18 and 15 km/h did not differ significantly between the groups, but the increase in step length per km/h velocity raise was greater in middle distance runners. Step lengths at these velocities were positively related to body mass, negatively to relative leg length (refer to Table 1). Even with body-mass-modified running economy values, there seems to be a poor correlation to step length. Furthermore, Morgan et al. (1987) found no significant relationship between change in VO_2 and change in SL at any 4 speeds (230, 245, 268, 293m/min), even though change in SL was substantial in some subjects. These data indicate that well-trained subjects can display a wide range of daily variation in RE that is unrelated to SL changes.

In subsequent research, Morgan et al. (1991) assessed the variability in RE and mechanics among trained male runners under the same testing conditions (same time of day, same footwear and nonfatigued state), and found high day to day RE reliability ($r = 0.95$). Stride to stride reliability for temporal (T), kinematic (KNM) and kinetic (KIN) measures was very high ($r = 0.91$-0.99), but day- to-day reliability was low for KIN (mean $r = 0.67$) compared with T and KNM (mean $r = 0.91$). However, further analyses showed that only 3 of the 22 biomechanical variables (peak resultant velocity at the ankle joint, step length and swing time) had statistically significant day to day differences. These results suggest that if the testing environment is controlled, stable measures of RE and most biomechanical variables can be obtained in trained runners. These findings were supported by Craib et al. (1994) where the reliability analyses indicated that the percentage of variation accounted for in step length across all speeds (160.8-214.8m/min) was high, indicating small within subject variability (2.22-2.50%). However, Cavanagh and Williams (1982) found that the average predicted optimal stride length expressed as a multiple of leg length (%LL) was 1.40 with considerable variability among subjects (range = 1.30-1.65). Low correlations were found between oxygen consumption at optimal conditions and SL ($r = 0.41$) and SL(%LL), ($r = 0.27$).

Recent research suggests that fatigue induced by prolonged or high intensity distance running may adversely influence the aerobic demand of running (Daniels, 1985; Cavanagh et al., 1985), and impacts on running economy and/or running mechanics. Brueckner et al. (1991) found that the energy cost of running increased with the distance covered, and was significantly higher immediately after a 32 or 42km run, but not after a 15km run. These findings were supported by Guezennec et al. (1995), who tested 11 trained male subjects after a 10 km triathalon run compared to after a 10 km run a week later at the same pace. They found significantly higher VO_2 values ($p<.005$) after the triathalon, indicating an increased energy cost of running due to the prior swim and cycling events. However, when Martin et al. (1987) measured RE one day after a hard training run, there were no changes in the 8 non-elite male runners.

To further investigate the effects of a prolonged maximal run, Morgan et al. (1990) tested 16 male distance runners after a 30 minute maximal run one, two and four days later with a 10 minute economy run. Results showed no significant differences in RE, and biomechanical analyses of kinematic variables revealed that, with the exception of plantar flexion angle at toe-off, gait characteristics remained unaltered after a prolonged maximal run.

Williams and Cavanagh (1987) provided support for the hypothesis that the mechanics of running have an influence on the metabolic costs. From their regression analysis a substantial portion of the variance in VO_2submax can be explained by biomechanical variables ($R^2 = 0.54$). It should be noted that in the above mentioned study, all the kinematics, with the exception of step length, were measured during overground running, unlike the majority of the previously cited studies, where the kinematic variables were derived from treadmill running. While Bassett et al. (1985) found no significant differences in VO_2 at speeds of 136-286m/min for treadmill versus overground running, the mechanical differences have yielded conflicting results (Williams, 1985). Frishberg (1983) found major biomechanical differences in the supporting leg during the support phase. During treadmill running, the angle of the lower leg at heel strike was significantly less vertical, and moved through a greater range of motion with a faster overall velocity. It was suggested that the moving treadmill helps bring the supporting leg back under the body during the support phase. In addition, speed may amplify these mechanical differences, as Williams (1985) reported that few significant differences were found for speeds under 300m/min. Therefore caution should be exercised when generalizing or comparing mechanical changes between overground and treadmill running.

In an attempt to determine the biomechanical correlates of economical running, Morgan et al. (1988) compared "high" economy (mean $VO_2 = 39.8$ ml/kg/min) versus "low" economy runners (mean $VO_2 = 45.0$ ml/kg/min) at a speed of 200m/min. The high economy group displayed significantly better RE values, lower stride time, lower absolute and relative swing time, longer absolute and relative stance time, shorter step length, less vertical oscillation of the center of mass, and less change in vertical velocity in two 10-min RE tests at 200m/min. These results concur with those of Cavanagh et al. (1977).

In studying the biomechanics of elite female runners, Williams et al. (1987) found that the most economical runners showed less leg extension near toe-off, contrary to elite male runners (Williams and Cavanagh, 1986). The higher economy group also showed less rapid knee flexion during swing, less vertical oscillation, more dorsiflexion of the foot and to a greater angle during support. Due to a small sample size (14) and unknown intraindividual stability of these biomechanical variables, generalization of these results is not warranted.

Other factors that may affect RE and kinematics include fatigue and training. Lake & Cavanagh (1990) proposed to determine the extent to which changes in RE due to training reflect alterations in running style. They assigned 15 recreationally active males to a training group (15-25 miles per week) for 6 weeks and a control group. In performing the two 10 minute RE post tests at 200m/minute over a four-day period, there were no significant changes in kinematic variables in either group. However, the training group demonstrated a significantly improved VO_2max, but significantly worse RE. These results suggest that while short term training enhances running performance (as measured by VO_2max increases), it does not necessarily improve running kinematics or RE. The improvement in running performance may be primarily due to physiological adaptations associated with an increase in VO_2max. The degree to which running mechanics influences RE remains unclear. Research has shown that biomechanical variables are a factor in running economy, yet to what degree can modifications in running style lower aerobic demand is not known. The following studies attempt to gain some insight into this question by examining the effects of intense or long duration bouts of running on RE and running mechanics.

As previously cited, when Morgan et al. (1990) tested 16 male runners, one, two and four days after a 30 minute prolonged maximal run at 90% VO_2max, they found no significant differences in RE. Only one biomechanical variable, plantar flexion angle at toe-off, was significantly greater one day versus four days after the maximal run. Again, Morgan et al. (1996) tested 10 well-trained male distance runners (10 minute economy run at 90% VO_2max), one, two and four days after 30 minutes of high intensity running at 90% VO_2max, and found no significant change in running economy or gait mechanics as measured by kinematic variables. It was concluded that among well-trained athletes, 30 minutes of higher intensity running does not elicit changes in VO_2 or running style over the short term in subsequent distance runs. However, in both studies, the RE and gait mechanics were re-tested one day after the maximal run, acute changes in running economy and/or mechanics may not have been detected. When Nicol et al. (1991) investigated the effects of marathon fatigue on both running kinematics and economy of 8 experienced endurance runners, (tested just before or after the marathon for 3 minutes at 75%, 2 minutes at 100%,and 1 minute at 125% of selected marathon speed), they found significant increases in energy expenditure and relative duration of the push-off phase at the 2 slowest speeds. Though, for the most part, these results failed to demonstrate that running kinematics and RE are interrelated in any systematic way when fatigue progresses, it suggests that some of the kinematic changes might reflect adaptations to fatigue, rather than failure to compensate for it. Williams' et al. (1988) study of changes in distance running kinematics with fatigue, showed a significant increase in step length, maximal knee flexion angle during swing, and an increased angle of the thigh with the vertical during hip flexion, which also occurs with increasing running speed (Williams, 1985). These findings were supported by Elliott and Ackland (1981) in their investigation of the effect of fatigue on running mechanics during a 10km race. Runners countered fatigue by changing stride length, rate, segmental body positions and reduced running velocity. A more extended lower limb increased the energy requirements of the recovery phase. Elliott et al. (1980) had found similar biomechanical changes starting at the last 100m of a 3000m time trial. Stride length decreased while stride rate increased to maintain constant velocity. The leg was more angled at foot strike, the thigh was less extended at the end of the support phase, and there was a greater forward trunk lean indicating adjustments to create greater efficiency (Cavanagh, 1977). It appears that there is a high degree of intraindividual variability in adaptive mechanical response to fatigue, but definite acute biomechanical changes have been observed.

In addition, Harris et al. (1990) found that delayed onset muscle soreness following a bout of downhill running, significantly reduced SL and knee range of motion 48 hours after, and significantly elevated perceived effort and RE 3 days later (Wilcox et al. 1989).

As previously stated, research has shown that training bouts and long distance running can and do affect RE and kinematics, yet to what degree and for how long do these changes remain, is still to be determined. This study therefore addresses the issue of high intensity interval training and its immediate effect on RE and running mechanics.

2.4 Running kinetics and economy

Research on the kinetics of running has been to a large extent descriptive, with little work focused on its relationship to running economy. Cavanagh and Lafortune (1980) measured the ground reaction forces and center of pressure (C of P) patterns of 17 subjects running at 270m/min. The subjects were classified as rearfoot or midfoot strikers according to the location of the C of P at the time of initial contact between foot and ground. The C of P path in the rearfoot strikers showed a continuous anterior movement during support, while for most of the midfoot strikers it migrated posteriorly in the first 20ms of the support phase. The range of peak values for the vertical component of ground reaction force (Fz) was considerable, indicating that some individuals can run at the same speed while exerting forces which are 30% lower than others. Differences between rearfoot and midfoot strikers anteroposterior component (Fy) were pronounced. In the midfoot group, the curves showed a fall to zero within 25ms of contact; a pattern completely absent in the rearfoot group. In a subsequent study designed to investigate how running kinetics relates to RE, Williams and Cavanagh (1987) found significantly smaller first peaks for vertical ground reaction forces at a speed of 216m/min in the high economy running group, and trends towards smaller anteroposterior and vertical peak forces. The correlation between

VO_2submax and the vertical ground reaction force was r= 0.56. Also, support time and peak medial force correlated positively with aerobic demand (r = 0.49 and 0.50 respectively), indicating that shorter support times and lower medial peak forces were associated with better RE. Intuitively, high ground reaction forces would be associated with increased energy costs, and in fact, in this study higher oxygen consumption values were positively related to greater vertical force peaks. It was suggested that differences in approach kinematics (prior to foot contact) may affect muscular demands both before and during support, thereby affecting RE. Furthermore, research by Miller et al. (1984) showed that as speed increased from 150m/min to 330m/min, the average maximal vertical "thrust" ranged from 2.2 - 2.8 body weight (BW), braking 0.3 - 0.5BW and propulsion from 0.2 - 0.5BW, while average stance time decreased from 305ms to 185ms.

From their results of animal studies, Kram and Taylor (1990) suggested that it is the time available for developing muscular force that is important in determining energy cost. They reported a simple inverse relationship between the rate of energy used for running and the time the foot applies force to the ground during each stride. Their results support the hypothesis that it is primarily the cost of supporting the animal's weight and the time course of generating this force that determines the cost of running. This is a reasonable conclusion in that as speed increases, stance time decreases, and an individual's aerobic demands are greater.

In examining the biomechanics of elite female runners, Williams et al. (1987) found that rearfoot strikers showed lower maximal forces and longer support times compared to midfoot strikers. As well, the correlation between strike index (initial center of pressure position as measured as a % shoe length) and change in vertical velocity was 0.69, indicating that a more posterior heel strike is associated with a smaller change in vertical velocity. These findings also lend support to Kram and Taylor's (1990) hypothesis on the energetics of running. It is interesting to note that the calculation of the asymmetry index for ground reaction forces were greatest for the mediolateral forces and strike index. For instance, the gross asymmetries reflected by reduced peak vertical force and a forefoot strike on the right side of one subject was due to a groin injury on the right side. Cavanagh et al. (1985) found that a male athlete "A" displayed a significantly greater degree of supination at foot strike on the right side, predisposing him to inversion sprains. It was found that these anomalies were more exaggerated during a fatiguing run. In examining the foot - ground reaction forces and the pressure distribution patterns, Cavanagh et al. (1985) found that athlete A showed a rearfoot strike on the left side, and a midfoot strike on the right. The peak vertical ground reaction force was over 4.1 body weight (BW) on the right side compared to 2.7BW on the left. These large differences disappeared when athlete A ran at the same speed (357.6m/min) with training shoes rather than his racing shoes. Results of the plantar pressure distribution pattern for athlete A showed highest peak pressures on the lateral aspect of the heel and midfoot during the first 20ms after footstrike, apparently a consequence of the exaggerated supinatory position of the foot at heel strike, whereas in the forefoot there was a more even distribution of pressures except for a peak in the region of the hallux in late support. The results of these studies highlight the inter and intraindividual differences in running kinetics.

Implications for shoe design requirements to provide both stability and shock absorption along the lateral border of the shoe, as well as midsole compliance in this case, to accommodate athlete A's running style demonstrates how information about an individual's running kinetics may be of value in improving his/her performance and reduce the risk of injury. However, more experimental work needs to be done to identify basic running style parameters, that is, create a data base of normative values, and how modifications in any of these biomechanical variables will impact on a runner's economy and performance.

A number of studies have shown that while mean within-subject differences in running economy and mechanics may appear to be minimal, ranges of individual differences are surprisingly large, and of a magnitude not to be ignored. (Morgan et al. 1991; 1987; Daniels et al. 1984). In particular, Morgan et al. (1991) found that while stride-to-stride reliability for kinetic measures was very high ($r = 0.91 - 0.99$), day to day reliability was lower ($r = 0.28 - 0.88$). In an attempt to determine what factors could alter running mechanics and RE, Morgan et al. (1990) tested 16 male runners, one, two and four days after a 30 minute prolonged maximal run. They found no significant differences in the running kinetics and RE of these moderately trained males. Whether a minimum time delay of one day after the maximal run may have erased subtle mechanical disruptions needs to be further investigated. As previously stated, fatigue did negatively impact on the running mechanics of collegiate athletes (Williams et. al. i988), and Stewart et al. (1984) found increasing trends in the first maximum vertical force and average medial-lateral force exhibited by 12 skilled runners performing 10 trials under a) no previous work b) 1/2 hour running bout c) 1 hour running bout conditions.

In fact, when Pizza et al. (1994) compared changes in RE, foot impact shock and run performance after 10 days of increased training, they found that VO_2 during the RE test was significantly higher day 11, as was foot impact shock (FIS). This increase in FIS indicates a decrease in the attenuation of force during submaximal running, which would theoretically increase a runner's risk of injury. However, to what extent these changes in running kinetics can be related to metabolic costs remains to be determined.

2.5 Mechanical power and running

It has been suggested that perhaps a global mechanical descriptor of the output of the neuromuscular system (total body mechanical power output), would be more closely associated with RE, which is considered a global indication of the physiological demand of running (Morgan et al. 1989). One would expect that more economical runners would display lower relative mechanical power outputs at a given speed, as the movement of the body would be made in such a way as to minimize the amount of mechanical work done.

In fact, when Chapman et al. (1985) compared one subject's preferred running style to an exaggerated knee flexion, hip flexion, straight lower limbs and stiff knees, it was found that the "normal" style is preferred partly because the between-segment energy transfers occur in a non-competing way (ie) positive and negative powers at different joints do not cancel out before they are integrated over time. Due to this problem, it was suggested that the within and between energy segment measure is an inaccurate reflection of the muscular cost. Since the total body mechanical impulse was least for the preferred style and much greater for the "stiff knees", this indicates the body's preference for minimizing muscular involvement as represented by a force-time integral. However, a mechanical work term that would be more reflective of actual metabolic cost would have to account for the differential cost of the concentric, and eccentric work, and antagonistic co-contraction. But few studies have been able to provide direct evidence that variations in mechanical power output explain interindividual differences in economy, even though RE is closely correlated ($r > 0.86$) with average mechanical power expressions at varying speeds (Shorten et al. 1981).

Taylor (1986) suggested that mechanical power or work cannot explain economy variations since the mechanical cost of locomotion can be predicted from the speed, but is independent of the body mass of the individual. In contrast, the metabolic energy cost is dependent on body mass. Taylor (1985) proposed that it is the time course of force development during locomotion, rather than the mechanical work that the muscles perform, that determines the metabolic cost of locomotion.

In addition, Anderson (1996) has summarized the specific drawbacks with methods of estimating mechanical power (see Table 5 below), and points out that a given level of mechanical power may result in different metabolic costs depending on how the power was generated. Clearly, a major limitation of mechanical power calculations is their inability to account for isometric contributions of muscles during gait. For example, just the considerable muscular effort required to support the body weight would contribute little to the measured mechanical work output (Martin and Morgan, 1992).

Table 5. Drawbacks with Methods of Estimating Mechanical Power

Focus on net work not total work
Failure to account for limb movement and production of ineffective forces
Failure to differentiate between contributions of 1- and 2 -joint muscles
Failure to account for energy transfers between and within segments
Lack of precise measurement regarding the relative energy cost of positive and negative work
Inconsistencies in changes in efficiency with changes in velocity
No consideration of the differences in energy cost of muscle contractions at different velocities
Models used to estimate contributions of stored elastic energy have not been fully developed
Failure to consider internal friction
Failure to consider nonmuscular sources of negative power

There is no consensus as to which analytical methods give the most accurate or meaningful values (Williams, 1985). Cavagna et al. (1964; 1971) evaluated the power involved in running and walking based on center of mass movements, however, Winter (1979) developed a segmental method to include contributions from the moving limbs involving within and between segment energy transfer; where energy could be converted between kinetic and potential forms. Shorten (1986) further refined this segmental method to account for elastic strain energy (energy stored in the elastic tissues as eccentric muscular contractions occur). Williams and Cavanagh (1983) developed a model for the estimation of total mechanical power (PTOT) during distance running that took into account the influences of energy transfer, differences in positive and negative metabolic energy cost, elastic storage and return of energy, and non-muscular sources of work. They showed trends toward the expected relationship for groups of runners divided on the basis of submaximal oxygen consumption, and cited energy transfers between segments of the body as the main reason for differences in mechanical power between the groups.

Williams and Cavanagh (1987) also measured net positive power (TOTTR), the amount of energy transferred between segments assuming total transfer of energy throughout the whole body (ETR), and the power determined from movements of the center of mass (PCM). Measures of muscular efficiency (ME) - ratio of mechanical power to metabolic energy expenditure - were calculated from PTOT and VO_2submax. Also measured was the amount of energy transferred between leg segments and the trunk (LEGTR). Net positive power was one of three significant biomechanical predictors of economy in a multiple linear regression model of the 16 runners tested. Also, the least economical runners displayed a trend toward lower net positive power, lower total mechanical power, and greater between segment energy transfer than the less economical runners.

One of the ways used to identify the contributions of the segments and joints to running speed was to examine changes in torque, power and work as running speed increased. Michiyoshi et al. (1985) used standard link segment modelling to compute the joint angular velocities and net joint torques of the right ankle, knee and hip of 5 skilled male sprinters at 5 different speeds (160.8; 233.4; 391.2;

471.6; and 575.4m/min). Muscle mechanical power at each joint was calculated by taking the product of the torque and the joint angular velocity. Though there were no significant differences in the shape of the power pattern at each joint, except for the hip immediately after foot contact, the magnitude of power increased as running speed increased. However, no correlations were made to metabolic costs.

Heise and Martin (1990) investigated whether total mechanical power output computed with center of mass (CM), segment (SEG) and kinetic - based (KIN) models could account for a substantial portion of observed variability in aerobic demand (VO_2submax) of 16 well trained males running at 201m/min. Results showed none of the mechanical power output variables accounted for a substantial portion of the variability in RE. In a subsequent study, Martin et al. (1993) tested the hypothesis that mechanical power and angular impulse would correlate positively with aerobic demand, while energy transfers would correlate negatively. Results on 16 recreational male runners at a speed of 201m/min showed primarily positive correlations between aerobic demand and power estimates, but explained no more than 32% of the variability. Total body angular impulse also correlated positively with aerobic demand ($0.32 < r < 0.42$), but energy transfer expressions from the various analytical models showed no consistent relationship with RE. These results explained only a small proportion of the normal interindividual variability in RE at a given running speed.

Few studies have examined the effects of an exhaustive distance run on mechanical power output variables. One, two and four days following a 30 minute prolonged maximal run, Morgan et al. (1990) found no significant differences in average power output using the center of mass approach, nor in total body mechanical work using the segment-based approach.

Based on research evidence to date, it is apparent that the mechanical efficiency of running exceeds the efficiency of conversion of chemical energy to kinetic energy by muscles. Elastic energy stored during the eccentric contractions of running makes a substantial contribution to propulsion as it is released during subsequent concentric contractions (Anderson, 1996). There appears to be considerable variability between individuals in the ability to utilize elastic energy (Williams, 1990), which suggests that this could be one source of the differences in metabolic costs associated with running at a given speed. To the extent that elastic strain energy can be recovered or the contractile mechanism potentiated, contributions to mechanical power from concentric muscular contractions should be reduced. Cavanga et al. (1971) estimated that oxygen consumption during running was reduced by 30% to 40% due to contributions from elastic storage and return of energy.

Because of the difficulties in accurately assessing a global descriptor such as mechanical power and its relationship to metabolic costs, this study focuses on how the kinematic biomechanical variables used by Williams and Cavanagh, (1987); Morgan et al.(1985;1990;1991;1996); Lake and Cavanagh (1990), and Nicol et al. (1991) are affected by acute intense interval training bouts. The results will be compared to the above-mentioned studies.

3. Methods

3.1 Subjects

Twelve highly trained elite male runners volunteered for this study. Subjects signed a consent form prior to participating in the investigation. Four subjects qualified for the 1996 Canadian Olympic Trials, and one subject was a Canadian record holder in the triathlon. Based on the Mercier Scoring Tables (Mercier 1994), personal best times were rated between 612 and 840 points (mean 727 ± 82 points).

Table 6 shows the physical and training characteristics. The subjects were lean with sum of 6 skinfolds equal to 44.8 ±5.0 mm. Skinfold thickness was measured at six sites (chest, triceps, supra-iliac, subscapular, thigh and abdomen) and converted to percent fat (Yuhasz, 1974). All subjects participated in 5 testing sessions which included: (1) treadmill accommodation runs; (2) a VO_{2max} test; (3) and three interval training sessions with RE tests at 200 and 268 m/min.

Table 6 Physical and training characteristics (n = 12)

Variable	Mean	SD	Range
Age (years)	24.8	5.1	18 - 34
Mass (kg)	69.2	6.5	60.5 - 82.3
Height (cm)	180.3	7.3	168.9 - 191.5
Sum of six skinfolds (mm)	44.8	5.0	36.7 - 52.0
Fatness (%)	8.0	0.5	7.2 - 8.7

VO_{2max} (L/min)	5.01	0.53	4.45 - 6.00
VO_{2max} (ml/kg/min)	72.5	4.3	64.3 - 80.5
HR_{max} (bpm)	189	11	172 - 208
Training (years)	7.6	4.5	1.0 - 17.0
Training (km/week)	72.5	23.1	40.0 - 120.0
Personal Best (Mercier points)	727	82	612 - 840

3.2 Testing protocols

Session 1: Treadmill accommodation runs

Since previous research has determined that treadmill accommodation runs of 30 to 60 minutes are required for subjects to settle into a consistent running pattern (Cavanagh and Williams 1982; Schieb 1986), all subjects performed an accommodation session on a calibrated, Quinton Q65 treadmill (Quinton instrument Co.). Subjects warmed-up at 200 m/min for 5-min, and then ran three 10-min bouts at 268 m/min with 5-min recovery between runs.

Session 2: Determination of VO_{2max} and velocity for the three interval workouts

Approximately 4-5 days after the treadmill accommodation session, subjects performed a VO_{2max} test. Measurements were averaged every 20 seconds using a SensorMedics 2900 metabolic cart (SensorMedics Corp., Yorba Linda, CA). After a standard 5-min warmup (201 m/min), subjects ran at 215 m/min for 1-min at 0% grade. Treadmill speed was increased 13.4 m/min (0.5 mph) every minute while the grade remained at 0%. The test ended when subjects reached volitional exhaustion. HR was recorded every 5 seconds using a Polar Vantage XL heart rate monitor (Polar Electro Oy, Finland). Peak VO_2 was determined from the highest 60-s period and was designated as VO_{2max}. The VO_{2max} averaged 72.5 ±4.3 ml/kg/min (5.01 ±0.53 L/min). This value is consistent with VO_{2max} data reported previously for well-trained and elite middle distance runners (Daniels et al. 1977; Morgan et al. 1996). Maximum HR values ranged from 172 to 208 bpm. Time to exhaustion on the treadmill varied from 10.9 to 13.7 minutes (mean 12.3 ±0.9 minutes). When running on a track compared to a level treadmill, Pugh (1970) suggested a reduction in speed by 4% to account for differences in oxygen cost associated with overcoming wind resistance during overground running at 360 m/min. Thus, we reduced the final treadmill velocity on the VO_{2max} test by 4% in order to establish the speed for the 10 x 400-m interval workouts.

Sessions 3-5: RE tests - pre and post workouts

In order to minimize daily variation in running economy within individuals and to avoid any circadian influences (Daniels et al. 1984; Morgan et al. 1994), subjects performed a total of three interval workouts at each speed, and were tested at the same time each day wearing the same shoes. Subjects refrained from eating for two hours prior to each session.

A RE test was performed prior to and after each interval workout for both speeds. Temperature in the lab was controlled between 20 and 23 degrees C. After a 5-min warm-up at 201 m/min and stretching, subjects ran at 200 and 268 m/min (0% grade) for 6-min with a five minute passive recovery between each RE test. RE was calculated in ml/kg/min and L/min by averaging the VO_2 during the last three minutes of each bout. Post test RE values were adjusted to account for changes in body mass due to the 10 x 400-m interval session.

The interval workouts were performed indoors on a 200-m banked track with a mondo-surface. Subjects ran 10 x 400-m with active recovery period (60, 120, 180 s) randomly assigned. The RE tests were performed 10-min prior to and following each workout. Mean environmental conditions in the fieldhouse for temperature, barometric pressure, and relative humidity were: 23.4 ±2.4 degrees C, 756 ±6.6 mm Hg, and 62 ±7.2%. Subjects ran alone with verbal encouragement and 200-m split times provided by the investigators. A minimum of four days recovery was allowed between workouts. Heart rate was continually recorded using a Polar Vantage XL monitor using 5 s recording intervals. Peak HR per repetition and minimum HR during each recovery were recorded.

Kinematic variables were measured on 11 of the 12 subjects during the last three minutes of the pre and post RE tests (200 and 268m/min). Reflective markers were secured on the bony landmarks of the right metatarsal, heel ankle, knee, hip, elbow, wrist, shoulder and just below the right earlobe. Fixed coordinate references were placed on the treadmill frame. Subjects were filmed sagittally using a high speed F-cam (EG&G Reticon) camera at 120Hz for at least one complete stride cycle (heel strike to heel strike). This recorded data was then digitized using the Ariel Performance Analysis System, filtered and smoothed for all the selected variables (refer to Table 2).

4. Statistical Analysis

The experimental design used for each of the seven kinematic dependent variables was a univariate repeated measures Anova with subjects (S) crossed with recovery (R) and pre-post test (T) and speed (SP). The Lee notation for this design is $\mathbf{S_{12} \times R_3 \times T_2 \times SP_2}$. The dependent variables measured were maximum knee flexion in support (KFLEX), minimum knee velocity during stance (KVEL), maximum plantar flexion angle at toe-off (PFLEX), shank angle at heel strike (SANG), mean trunk angle during stride cycle (TANG), mean vertical oscillation of center of mass (VOSC), and stride cycle length (SL). As stated previously, these variables were chosen in accordance to studies done by Williams and Cavanagh (1987), Morgan et al. (1985;1990; 1991; 1996), and Nicol et al. (1991) in order to compare results. The data was analyzed using Systat 5.05 by SPSS Inc.

5. Results

Biomechanical variables:

Due to technical difficulties, data on 5 of the 12 subjects filmed was incomplete and not included in the analysis. Missing markers and/or too high a recording speed (480Hz instead of 120Hz) prevented us from obtaining data for a complete stride cycle (heel strike to heel strike) on these trials.

For the seven subjects analyzed, a summary of the descriptive statistics of all the kinematic variables is provided in Table7 below, and Tables A1 to A7 in the Appendix A present the raw data for each of the dependent variables measured.

Table 7: Biomechanical variables during RE tests prior to and following the interval workouts (mean ± SD)

Dependent variables	RE test m/min.	Recovery Intervals 60 sec.	120 sec.	180 sec.
KFLEX	Pre 200	39.9 ± 6.1	43.2 ± 1.7	42.0 ± 5.3
	Post 200	47.3 ± 9.4	46.5 ± 10.8	46.4 ± 9.4
	Pre 268	44.6 ± 4.3	44,2 ± 1.8	37.7 ± 15.7
	Post 268	42.9 ± 5.1	42.1 ± 5.7	46.0 ± 3.7
KVEL	Pre 200	93.4 ± 8.4	100.2 ± 36.3	106.0 ± 37.4
	Post 200	108.6 ± 24.9	82.9 ± 11.1	90.8 ± 13.4
	Pre 268	122.2 ± 30.2	106.8 ± 32.9	97.8 ± 19.1
	Post 268	129.6 ± 33.7	101.9 ± 11.4	127.3 ± 38.1
PFLEX	Pre 200	77.6 ± 8.8	82.1 ± 2.7	81.5 ± 7.0
	Post 200	78.8 ± 15.1	76.3 ± 9.2	81.2 ± 4.4
	Pre 268	82.6 ± 3.2	82.0 ± 6.3	69.6 ± 29.9
	Post 268	81.2 ± 7.4	80.8 ± 2.2	84.7 ± 3.9
SANG	Pre 200	9.2 ± 2.3	10.1 ± 2.5	8.3 ± 4.6
	Post 200	12.5 ± 6.8	11.0 ± 3.6	9.7 ± 6.9
	Pre 268	13.4 ± 2.9	14.1 ± 3.9	11.3 ± 5.8
	Post 268	14.9 ± 1.4	12.5 ± 2.3	13.6 ± 7.3
TANG	Pre 200	1.8 ± 6.1	2.8 ± 2.7	2.9 ± 3.9
	Post 200	6.2 ± 7.5	0.7 ± 5.8	3.8 ± 4.1
	Pre 268	4.4 ± 4.9	1.9 ± 4.9	3.3 ± 3.6
	Post 268	2.7 ± 2.5	4.5 ± 2.1	4.5 ± 4.9
VOSC	Pre 200	11.6 ± 1.2	11.2 ± 1.9	12.2 ± 1.8
	Post 200	10.6 ± 2.3	10.3 ± 2.1	13.2 ± 3.9
	Pre 268	11.8 ± 0.9	11.9 ± 1.8	12.3 ± 2.1
	Post 268	11.9 ± 1.9	12.5 ± 1.6	13.2 ± 2.2
SL	Pre 200	2.2 ± 0.4	2.2 ± 0.1	2.3 ± 0.1
	Post 200	2.3 ± 0.5	2.1 ± 0.3	2.3 ± 0.2
	Pre 268	2.9 ± 0.7	2.9 ± 0.3	2.9 ± 0.3
	Post 268	2.8 ± 0.6	3.0 ± 0.6	3.0 ± 0.4

From Table 7, it can be seen that there were relatively large standard deviations for all of the testing conditions for minimum knee velocity during stance (KVEL), indicating substantial intersubject variability. The results of the repeated measures analysis of variance show that there were near significant differences ($p = 0.054$) for this variable between the two speeds tested (with an average of 97.0 ± 19.9 cm/s and 114.3 ± 27.6 cm/s at 200 and 268m/min respectively). In addition, significant differences were found in the shank angle at heel strike (SANG) and stride length (SL), $p = 0.03$ and $p = 0.00$ respectively. Average shank angle at heel strike was 10.1 ± 4.5 and 13.3 ± 3.9 degrees at 200 and 268 m/min. respectively. Average SL was 2.2 ± 0.3 and 2.9 ± 0.5 meters at 200 and 268 m/min. respectively (Figures 2, 3, and 4).

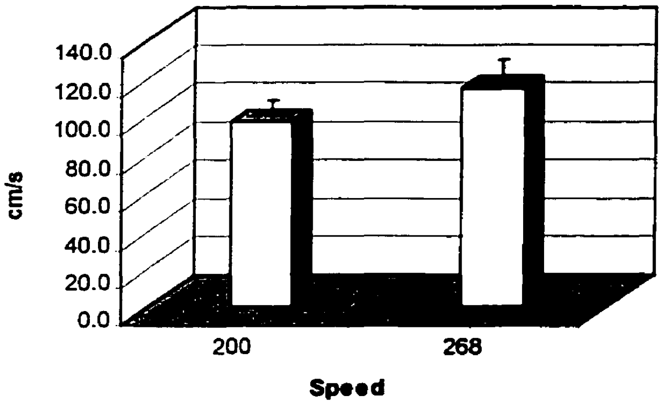


Figure 2. Average minimum knee velocity during stance (n=7)

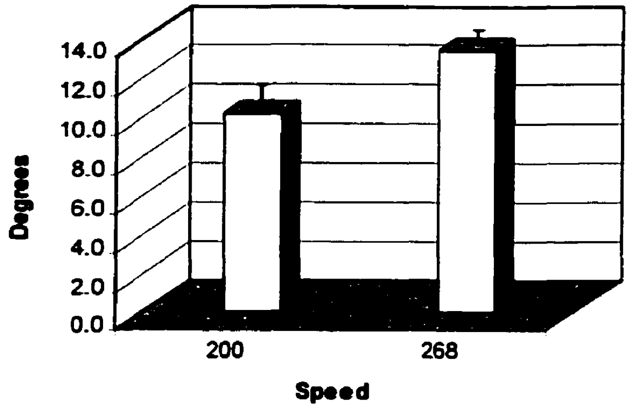


Figure 3. Average shank angle at heel strike (n=7)

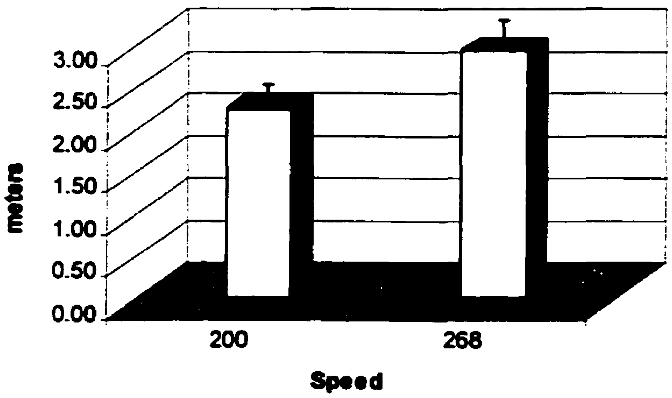


Figure 4. Average stride length (n=7)

Refer to Tables A8 to A14 in Appendix A for the repeated measures Anova for each variable. The repeated measures analysis for VOSC (Table A13) identified a non-significant but substantial trend of increasing vertical oscillation of the center of mass as speed increased ($p = 0.075$). For the main effect of recovery, there were non-significant mixed results for two of the kinematic variables. Vertical oscillation of the center of mass (VOSC) showed increases between the recovery conditions 60s and 120s (both means equal to 11.5cm) and 180s ($\bar{x}$ = 12.7cm), $p = 0.172$. Minimum knee velocity during stance demonstrated a mixed effect for recovery ($p = 0.154$), where the highest average minimum velocity of the knee occurred in the 60s recovery condition ($\bar{x}$ = 113.5cm/s), while the lowest average minimum velocity of the knee occurs in the 120s recovery condition ($\bar{x}$ = 97.9cm/s), with mean KVEL values of ($\bar{x}$ = 105.5cm/s) for the 180s recovery condition.

There were no significant changes in any of the kinematic measures for the main effects of pre and post test and recovery conditions. Table 8 below provides a summary of p values for all the biomechanical variables measured.

Table 8. Summary of p values from repeated measures mAnova for all biomechanical variables

Variable	S	P	R	S x P	S x R	P x R	S x P x R
KFLEX	0.695	0.326	0.97	0.32	0.499	0.498	0.538
KVEL	0.054	0.824	0.154	0.256	0.705	0.428	0.097
PFLEX	0.114	0.474	0.622	0.305	0.726	0.511	0.173
SANG	0.036*	0.103	0.634	0.471	0.586	0.493	0.473
TANG	0.833	0.222	0.551	0.478	0.536	0.698	0.102
VOSC	0.075	0.798	0.172	0.244	0.033*	0.556	0.371
SL	0.000*	0.973	0.777	0.863	0.711	0.943	0.494

* $p < 0.05$

There was a significant interaction effect between speed and recovery conditions ($p = 0.033$). To further analyze this result, a post hoc test of effects with two User Defined Contrasts was chosen (given that the means for R1 and R2 were 11.5cm, and 12.7cm for R3). Using the appropriate Bonferroni adjustments, (which yielded a conservative p value), the contrast between recovery condition 2 and 3 again resulted in a non-significant effect. This was previously indicated in the main effect for recovery. These results indicated an increasing vertical oscillation of the center of mass as the speed increased and as the rest recovery interval increased from 120s to 180s, though not statistically significant ($p = 0.092$). Refer to Table 15A for the VOSC contrasts.

Physiological variables:

From the same cohort sample, Zavorsky et al. (1998) found that VO_2, HR, and RER changed significantly from pre to post test ($p < 0.01$) at both RE velocities independent of the recovery interval. Averaged across recovery conditions, VO_2submax increased ($p < 0.01$) by 2.0 and 1.4ml/kg/min at RE speeds of 200 and 268m/min respectively. The RE data prior to the interval training session showed a mean VO_2submax of 38.5ml/kg/min at 200m/min and 53.1ml/kg/min at 268m/min, indicating speed as a significant main effect in RE. There were no significant interaction effects.

6. Discussion

This current study addressed the question as to how running mechanics varies across two different speeds (200 and 268m/min), and to what degree intense interval training sessions affect running mechanics. Kinematic changes were measured by the following biomechanical variables shown by previous research to be correlated with RE (Table 4): minimum knee flexion in support (KFLEX), minimum knee velocity during support (KVEL), maximum plantar flexion angle at toe-off (PFLEX), shank angle at heel strike (SANG), mean trunk angle during stride cycle (TANG), mean vertical oscillation of center of mass (VOSC), and stride cycle length (SL).

Published studies have shown that among well-trained runners, a strong relationship exists between 10km run time and velocity at VO_2max that appears to be mediated to a large extent by RE (Morgan et al. 1989). Furthermore, Williams and Cavanagh (1987) have indicated that the mechanics of running influences metabolic cost, and a substantial portion of the variance in $VO_2submax$ is attributable to biomechanical variables ($R^2 = 0.54$).

The results of our study showed that speed had a significant effect ($p = 0.000$) on SL. The average SL of 2.3m at 200m/min increased to an average of 2.9m at 268m/min (Figure 2). These findings concur with Cavanagh and Kram (1990) who argued that the mechanism for increasing speed appears to be one that maintains stride frequency, thereby necessitating an increase in stride length. However, Morgan et al. (1987) found no significant relationship between change in VO_2 and change in SL at 4 different speeds (230, 245, 268, and 293m/min). In fact, step length itself has been shown to have a significantly high day to day variability (Morgan et al. 1991). Though there were substantial changes in RE (pre and post test for both running speeds), we cannot conclude that they are related to the changes observed in SL. It was found that neither pre and post test nor recovery conditions had any significant effect on SL (Table 8), whereas VO_2 had changed significantly at both RE velocities (Zavorsky et al. 1998). These results are in accord with Brueckner et al. (1991) and Guezennec et al. (1995) where significantly higher VO_2 values were found due to the immediate prior level of exertion (long distance running - 32 or 42km, and a triathlon respectively).

Speed had a significant effect on the shank angle at heel strike ($p = 0.036$). As the speed changed from 200 to 268m/min, the average shank angle at heel strike was significantly less vertical (10.1 degrees at 200m/min versus 13.3 degrees at 268m/min, Figure 3). Frishberg (1983) found that during treadmill running, the angle of the lower leg at heel strike was significantly less vertical, and moved through a greater range of motion with a faster overall velocity than for overground running. Our treadmill running measures were comparable to those of Williams and Cavanagh (1987), where they found a mean SANG of 7.36 degrees at 214m/min for overground running. Furthermore, electromyography studies have shown that the main muscle group that appears to increase the speed of gait are the hip flexors, which are closely linked to the knee extensors in propelling the body forward while running (Mann et al. 1986). Our findings indeed show that as the speed increased, the SANG and KVEL also increased, indicating that subjects' lower limbs go through a greater range of motion (increasing lower leg extension at heel strike) and do this faster (increasing the minimum knee velocity during stance) as speed increases.

Our results for minimum knee velocity during stance reveal near significant differences ($p = 0.054$) between the two speeds, with an average KVEL of 96.9cm/s at 200m/min as opposed to 114.3cm/s at 268m/min (Figure 2). These results are comparable to Williams and Cavanagh (1987) who found an average KVEL of 107.6cm/s at 214m/min for overground running. According to Frishberg (1983), there should be a faster overall velocity for treadmill running. Our results do not demonstrate this clearly. The difficulties in identifying precise events such as heel strike and stance can impact on the values obtained for SANG and KVEL, and hence influence whether differences obtained for the various conditions were significant or not. Our results showed that the faster speed yielded significant changes in KVEL, SANG and SL, but there were also indications that pre and post test conditions affected SANG ($p = 0.103$), and recovery conditions affected KVEL ($p = 0.154$). There was also an interactive effect between recovery, test and speed conditions ($p = 0.097$). Many effects are suggested by these low p values, even though they were not statistically significant (perhaps due to the small sample size n=7). These changes may have been due to fatigue incurred as a result of the intense interval training sessions and varying recovery conditions. Previous research has resulted in controversial findings. Morgan et al. 1996 found no significant changes in running economy or gait mechanics one, two or four days after 30 minute high intensity running at 90% VO_2max. However, other studies found significant changes in some of the kinematic variables measured (Williams, 1985: Elliot et al. 1981;

Williams et al. 1988; and Nicol et al. 1991). These changes were perhaps due to acute fatigue, though for the most part these results could not be related in any systematic way to RE as fatigue progressed.

Our results showed a trend for the vertical oscillation of the center of mass to increase as the speed increased, and a significant interaction between recovery and speed ($p = 0.033$). Further analyses of VOSC revealed a non-significant positive effect between speed and recovery conditions of 120s and 180s. As we would intuitively expect the reverse to occur, these findings deserve further investigation. In fact, in this study, the recovery conditions did appear to influence the running mechanics, in particular, VOSC, independent of RE. As previously noted, Zavorsky et al. 1998 found no significant changes in RE due to the recovery intervals. Further research is indicated to clarify the relationship between recovery interval, RE and certain kinematic variables, to ascertain how fatigue indeed contributes to these changes. Our findings indicated a lack of any systematic or progressive changes in running mechanics due to pre and post test conditions or recovery intervals.

The lack of clear trends may be partly attributed to noticeable inter and intrasubject variability for many of the kinematic measures (Table 7). It is known that intraindividual running economy in trained subjects can vary by as much as 11% (Daniels et al. 1984). Presumably running mechanics can do the same. Step length has been shown to have significant day- to- day variability within individuals (Morgan et al. 1991). Cavanagh et al (1985) found substantial differences in foot strike, peak vertical ground reaction force and plantar pressure distribution in one elite athlete comparing left and right sides. These studies highlight the need to establish " norms" for the various kinematic and kinetic variables measured in assessing subjects' running mechanics. Running style considerations due to anthropometric and physiological limitations may in fact be adaptations that enhance rather than hinder running economy.

This study affirmed our hypothesis that speed significantly impacts on some kinematic variables (KVEL, SANG, and SL,), and to a degree has shown that pre and post test and recovery conditions creating a fatigued state altered two of the kinematic variables (KVEL and VOSC). However, none of the other kinematic variables measured were altered by speed or fatigue in any substantial way. Whether the significant kinematic changes that occurred reflect adaptations to fatigue, rather than a failure to compensate for it, is not clear. The interrelationship between metabolic and biomechanical markers of training and performance appears to be complex and somewhat individualistic.

7. Conclusions

It is clear that there is no simple relationship between RE and running mechanics. Providing answers as to whether intense interval training impacts on running technique needs some qualifying parameters. From this study, it appears that short bouts of intense interval training does not impact significantly on the running style of highly trained athletes. Perhaps further investigations using less trained individuals may lead to more pronounced changes in the biomechanical parameters that were assessed. These changes, due to intense interval and/or long duration training, could possibly be used to identify and subsequently alter uneconomical running styles.

This study did reveal some kinematic changes, which perhaps would be more substantial if post tests were conducted during or immediately following the intense training, since it appears that important mechanical changes may occur as fatigue progresses, but are not preserved after rest intervals. In addition, using longer intense training periods may produce more substantial changes in running mechanics that could assessed in terms of overtraining (a chronic maladaptation to training) implications. Furthermore, by establishing parameters of running mechanic "norms" for novice to elite athletes, one could prevent the development of poor running style patterns in novice runners, as well as use these “norms” as a diagnostic tool for predicting the likelihood of injury to all runners. This would ultimately lead to enhanced training techniques and performance. However, the remarkable fact remains that the human body is a resilient and resourceful machine, and some of the observed kinematic changes may well reflect the body’s adaptation to fatigue, rather than a failure to compensate for it.

Appendix A

Table A1. Maximum knee flexion in support (KFLEXdegs)

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268
AH	41.7	45.5	54.8	48.0	40.5	42.7	39.7	39.7	43.9	45.3	42.5	46.4
MO	40.9	41.2	46.0	45.2	42.3	42.4	37.3	43.4	49.3	50.6	43.3	48.2
LM	27.8	51.2	64.0	33.0	44.4	44.7	69.5	47.2	33.0	42.5	67.7	49.3
LS	41.3	40.8	36.9	40.4	43.7	46.1	44.3	47.2	46.0	45.2	43.3	49.3
PC	42.1	43.9	43.6	41.6	45.5	45.9	48.9	30.6	42.8	42.7	42.6	42.6
PS	47.9	49.3	47.3	46.4	44.0	45.4	43.4	43.4	39.7	40.1	43.9	46.9
TG	37.8	40.1	38.7	45.8	42.1	41.9	42.3	43.1	39.4	40.9	41.5	39.6

Table A2.Minimum knee velocity during stance (KVEL cm/s)

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268
AH	77.7	83.1	94.6	107.3	87.7	74.6	71.3	101.5	68.6	91.4	65.9	86.1
MO	90.0	140.4	90.6	144.7	150.3	149.7	98.4	101.0	158.1	73.4	90.5	76.9
LM	94.5	110.7	132.5	129.3	150.3	100.4	91.8	98.4	158.1	79.4	107.8	166.1
LS	96.4	176.1	130.8	187.0	90.2	124.7	68.1	106.2	74.6	125.4	85.7	177.2
PC	105.7	123.4	82.3	118.4	54.4	63.1	78.6	86.9	100.9	110.2	88.1	110.8
PS	95.4	123.1	141.0	141.3	82.3	141.1	90.1	123.8	84.1	113.8	96.7	136.9

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268
TG	93.8	98.6	88.7	79.8	86.1	94.2	81.7	95.3	97.8	90.7	100.7	136.9

Table A3. Maximum plantar flexion angle at toe off (PFLEXdegs)

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268
AH	82.4	83.5	86.8	78.3	80.2	80.9	78.8	78.8	79.4	79.2	80.0	82.0
MO	78.0	79.7	83.2	80.3	81.9	81.9	80.7	80.3	93.6	85.9	82.2	82.2
LM	62.7	81.1	45.6	66.7	81.6	69.5	74.9	79.8	71.2	69.8	78.6	90.0
LS	79.7	81.1	81.0	85.7	79.8	82.2	76.4	78.5	84.0	85.2	78.6	80.5
PC	70.3	81.4	84.1	87.0	87.7	88.4	56.8	80.9	85.3	85.3	86.0	85.8
PS	89.8	89.4	90.6	88.9	80.8	88.1	84.5	84.5	79.2	79.0	87.8	82.8
TG	80.5	82.2	80.4	82.0	82.6	83.2	81.8	83.0	77.9	78.8	75.4	89.8

Table A4. Shank angle at heel strike (SANGdegs)

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268
AH	4.9	9.5	24.9	15.5	9.6	14.5	8.6	12.9	9.0	16.5	9.8	16.0
MO	9.6	16.3	8.9	13.3	10.1	9.7	7.5	11.7	12.3	9.6	6.5	8.8
LM	10.6	12.5	12.5	15.6	8.6	17.0	9.4	13.8	-1.2	2.0	3.1	5.6

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268
LS	8.2	13.0	9.0	12.9	7.9	15.3	15.9	13.6	7.9	7.3	10.5	10.0
PC	8.4	12.2	3.3	16.2	8.4	8.8	8.2	8.5	9.3	10.5	7.2	9.2
PS	11.9	11.9	12.4	16.3	10.8	13.7	11.5	11.4	8.2	14.0	6.7	19.1
TG	10.9	18.4	16.4	14.3	15.3	19.9	16.1	15.6	12.6	19.1	24.4	26.5

Table A5. Mean trunk angle during stride cycle (TANGdegs)

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268
AH	11.1	10.2	22.5	2.2	5.1	6.8	2.1	4.9	5.4	4.3	3.4	-0.7
MO	6.0	4.8	5.4	4.8	5.2	5.2	5.5	6.2	8.6	7.9	8.5	8.4
LM	-3.2	11.0	7.6	-2.2	1.9	-7.7	1.3	2.5	-0.0	0.0	5.8	5.8
LS	2.4	4.1	3.2	4.9	5.5	4.5	3.7	3.7	4.1	7.3	5.1	7.2
PC	-7.6	-3.1	0.8	1.8	-1.2	-0.9	-12.0	8.1	-3.6	2.0	-2.5	-2.5
PS	0.9	0.6	1.6	4.2	-0.2	3.7	2.4	3.2	2.8	2.4	7.1	1.4
TG	3.3	3.1	2.4	3.0	3.7	2.2	2.3	2.7	3.6	2.9	-0.8	9.5

Table A6. Mean vertical oscillation of center of mass (VOSCcm)

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268
AH	12.4	12.6	6.5	9.8	9.1	11.2	10.7	12.8	9.8	12.2	10.5	10.6
MO	13.2	12.8	10.4	13.6	14.4	14.4	11.7	14.9	15.4	14.9	16.3	16.1
LM	9.7	11.5	8.9	11.2	9.7	9.4	9.7	13.8	12.5	13.9	15.7	15.1
LS	12.3	12.6	12.7	12.0	12.3	12.8	10.9	13.1	13.4	13.4	10.2	12.7
PC	11.8	11.6	13.2	15.0	11.6	11.4	6.2	10.5	11.3	10.7	11.3	12.0
PS	10.5	11.6	11.2	12.2	11.3	13.9	12.8	12.0	11.3	12.5	9.2	10.8
TG	11.0	10.2	11.4	9.9	9.6	10.8	10.4	10.7	11.3	8.7	19.4	15.0

Table A7. Stride cycle length (SLm)

SUBJECT	60 S RECOVERY				120 S RECOVERY				180 S RECOVERY			
	PRE		POST		PRE		POST		PRE		POST	
	200	268	200	268	200	268	200	268	200	268	200	268
AH	2.2	2.4	1.8	2.7	2.2	2.9	2.3	2.7	2.2	2.7	2.2	3.4
MO	2.3	2.7	2.2	2.7	2.0	2.7	2.2	2.8	2.4	3.1	2.6	3.5
LM	1.7	4.4	3.3	4.2	2.3	3.5	2.4	2.8	2.6	3.4	2.2	2.8
LS	2.3	2.8	2.1	2.7	2.3	2.9	2.2	2.9	2.3	2.9	2.2	2.4
PC	2.8	2.7	2.3	2.1	2.3	3.2	1.5	4.4	2.3	2.7	2.3	3.0
PS	2.1	2.7	2.1	2.6	2.4	2.6	1.8	2.7	2.2	2.8	2.1	2.5
TG	2.2	2.7	2.2	2.7	2.1	2.6	2.2	2.8	2.2	2.7	2.7	3.1

Table A8. Repeated measures ANOVA for KFLEX

Source	SS	df	MS	F	P	G-G	H-F
RECOVERY	2.398	2	1.199	0.031	0.97	0.962	0.97
Error	471.509	12	39.292				
PREPOST	76.746	1	76.746	1.145	0.326	.	.
Error	402.28	6	67.047				
SPEED	8.24	1	8.24	0.17	0.695	.	.
Error	291.486	6	48.581				
RECOVERY *PREPOST	19.249	2	9.625	0.74	0.498	0.464	0.488
Error	156.065	12	13.005				
RECOVERY *SPEED	13.358	2	6.679	0.738	0.499	0.481	0.499
Error	108.649	12	9.054				
PREPOST *SPEED	204.538	1	204.538	1.175	0.32	.	.
Error	1044.324	6	174.054				
RECOVERY *PREPOST *SPEED	21.789	2	10.895	0.653	0.538	0.486	0.507
Error	200.115	12	16.676				

Table A9 - Repeated measures ANOVA for KVEL

Source	SS	df	MS	F	P	G-G	H-F
RECOVERY	3690.503	2	1845.252	2.273	0.154	0.161	0.154
Error	8119.649	10	811.965				
PREPOST	33.523	1	33.523	0.055	0.824	.	.
Error	3066.734	5	613.347				
SPEED	7925.006	1	7925.006	6.311	0.054	.	.
Error	6278.759	5	1255.752				
RECOVERY *PREPOST	858.141	2	429.071	0.925	0.428	0.422	0.428
Error	4638.753	10	463.875				
RECOVERY *SPEED	462.35	2	231.175	0.362	0.705	0.649	0.704
Error	6390.286	10	639.029				
PREPOST *SPEED	311.805	1	311.805	1.647	0.256	.	.
Error	946.758	5	189.352				
RECOVERY *PREPOST *SPEED	774.89	2	387.445	2.968	0.097	0.122	0.102
Error	1305.591	10	130.559				

Table A10 - Repeated measures ANOVA for PFLEX

Source	SS	df	MS	F	P	G-G	H-F
RECOVERY	60.709	2	30.355	0.495	0.622	0.565	0.598
Error	736.409	12	61.367				
PREPOST	6.048	1	6.048	0.583	0.474	.	.
Error	62.267	6	10.378				
SPEED	120.72	1	120.72	3.41	0.114	.	.
Error	212.395	6	35.399				
RECOVERY *PREPOST	107.37	2	53.685	0.71	0.511	0.484	0.511
Error	907.147	12	75.596				
RECOVERY *SPEED	22.232	2	11.116	0.329	0.726	0.685	0.726
Error	405.522	12	33.794				
PREPOST *SPEED	25.103	1	25.103	1.257	0.305	.	.
Error	119.784	6	19.964				
RECOVERY *PREPOST *SPEED	59.577	2	29.789	2.036	0.173	0.189	0.177
Error	175.597	12	14.633				

Table A11 - Repeated measures ANOVA for SANG

Source	SS	df	MS	F	P	G-G	H-F
RECOVERY	10.371	2	5.185	0.512	0.634	0.549	0.549
Error	40.515	4	10.129				
PREPOST	50.15	1	50.15	8.255	0.103	.	.
Error	12.151	2	6.075				
SPEED	85.47	1	85.47	26.42	0.036	.	.
Error	6.47	2	3.235				
RECOVERY *PREPOST	39.803	2	19.901	0.848	0.493	0.457	0.464
Error	93.906	4	23.477				
RECOVERY *SPEED	22.411	2	11.205	0.613	0.586	0.555	0.586
Error	73.105	4	18.276				
PREPOST *SPEED	9.62	1	9.62	0.777	0.471	.	.
Error	24.767	2	12.383				
RECOVERY *PREPOST *SPEED	17.297	2	8.649	0.908	0.473	0.441	0.442
Error	38.082	4	9.52				

Table A12 - Repeated measures ANOVA for TANG

Source	SS	df	MS	F	P	G-G	H-F
RECOVERY	26.586	2	13.293	0.633	0.551	0.495	0.519
Error	209.967	10	20.997				
PREPOST	15.652	1	15.652	1.944	0.222	.	.
Error	40.256	5	8.051				
SPEED	1.073	1	1.073	0.049	0.833	.	.
Error	108.792	5	21.758				
RECOVERY *PREPOST	5.587	2	2.793	0.372	0.698	0.582	0.592
Error	75.04	10	7.504				
RECOVERY *SPEED	20.773	2	10.387	0.665	0.536	0.504	0.536
Error	156.252	10	15.625				
PREPOST *SPEED	7.69	1	7.69	0.587	0.478	.	.
Error	65.508	5	13.102				
RECOVERY *PREPOST *SPEED	113.667	2	56.834	2.891	0.102	0.132	0.118
Error	196.587	10	19.659				

Table A13 - Repeated measures ANOVA for VOSC

Source	SS	df	MS	F	P	G-G	H-F
RECOVERY	27.845	2	13.923	2.048	0.172	0.181	0.172
Error	81.592	12	6.799				
PREPOST	0.367	1	0.367	0.072	0.798	.	.
Error	30.607	6	5.101				
SPEED	13.067	1	13.067	4.631	0.075	.	.
Error	16.93	6	2.822				
RECOVERY *PREPOST	7.481	2	3.741	0.616	0.556	0.555	0.556
Error	72.901	12	6.075				
RECOVERY *SPEED	7.6	2	3.8	4.611	0.033	0.05	0.037
Error	9.889	12	0.824				
PREPOST *SPEED	2.704	1	2.704	1.666	0.244	.	.
Error	9.738	6	1.623				
RECOVERY *PREPOST *SPEED	2.48	2	1.24	1.079	0.371	0.37	0.371
Error	13.788	12	1.149				

Table A14 - Repeated measures ANOVA for SL

Source	SS	df	MS	F	P	G-G	H-F
RECOVERY	0.095	2	0.048	0.258	0.777	0.747	0.777
Error	2.21	12	0.184				
PREPOST	0	1	0	0.001	0.973	.	.
Error	0.369	6	0.061				
SPEED	9.602	1	9.602	62.835	0	.	.
Error	0.917	6	0.153				
RECOVERY *PREPOST	0.015	2	0.007	0.059	0.943	0.857	0.88
Error	1.509	12	0.126				
RECOVERY *SPEED	0.167	2	0.083	0.351	0.711	0.629	0.659
Error	2.853	12	0.238				
PREPOST *SPEED	0.007	1	0.007	0.032	0.863	.	.
Error	1.271	6	0.212				
RECOVERY *PREPOST *SPEED	0.135	2	0.068	0.748	0.494	0.479	0.494
Error	1.085	12	0.09				

Table A15. User Defined Contrasts

TEST FOR EFFECT CALLED: CONSTANT
C MATRIX

1	2	3	4	5
1.000	-1.000	1.000	-1.000	0.000

6	7	8	9	10
0.000	0.000	0.000	-1.000	1.000

11	12
-1.000	1.000

TEST OF HYPOTHESIS

S1 v S2 at R1
vs
S1 v S2 at R3

SOURCE	SS	DF	MS	F	P
HYPOTHESIS	15.630	1	15.630	2.196	0.189
ERROR	42.713	6	7.119		

Bonferroni correction - p = 0.378

TEST FOR EFFECT CALLED: CONSTANT

C MATRIX

1	2	3	4	5
0.000	0.000	0.000	0.000	1.000
6	7	8	9	10
-1.000	1.000	-1.000	-1.000	1.000
11		12		
-1.000	1.000			

TEST OF HYPOTHESIS

S1 v S2 at R2
vs
S1 v S2 at R3
Bonferroni correction - p = 0.092

SOURCE	SS	DF	MS	F	P
HYPOTHESIS	60.800	1	60.800	6.265	0.046
ERROR	58.229	6	9.705		

APPENDIX B

CONSENT FOR EXERCISE TESTING

I,____________________________(print name) authorize Dr. David Montgomery and Gerry Zavorsky to administer the exercise tests outlined below which will be used for research purposes. I understand that I may discontinue the testing if at any time I experience unusual discomfort. I understand that the staff conducting the tests will ask me to discontinue the tests if any indication of abnormal response to the tests becomes apparent. I understand that I will perform the tests as listed below and I have the opportunity to question and discuss the exact procedure to be followed.

TESTS TO BE PERFORMED

1) Treadmill accommodation: You will warm-up on the treadmill at 200 m/min (7:28 min per mile) for 5 minutes. Then after some stretching, you will perform three, 10 min runs at 268 m/min (6 min mile pace) with 5 minutes rest between.

1) Aerobic capacity (VO_{2max}): You will warm-up on the treadmill for 5 minutes at 200 m/min. Then after stretching, you will start at 213 m/min (8 mph) at 0% grade. Every minute, the speed will increase 0.5 mph keeping the elevation at 0%. You should run as long as possible so that a true value can be obtained.

2) Running economy test (12 tests total): You will run on the treadmill for 6 minutes at 7.5 mph, then rest 5 minutes, and then run on the treadmill for 6 minutes at 10 mph.

This will be done before each interval workout of 10 x 400-m. Then after each interval workout, the same two running economy tests will be performed again.

3) Interval workouts (3 total): You will run 10 x 400-m at the speed specified by the researcher(s), not faster, not slower. Active recovery (jogging between each interval) will be allowed and drinking water will also be allowed. 200-m split times will be given to everyone.

A video camera will be filming your biomechanical running gait during certain occasions

I acknowledge that I have read this form and I understand the test procedure to be performed and the inherent risk and I consent to participate. I understand that the data will be released only to the principal investigators unless I deem otherwise.

SIGNATURE OF SUBJECT:__________________DATE:

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