Work-energy analysis of running triathletes under bike/run and run conditions.

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WORK-ENERGY ANALYSIS OF RUNNING TRIATHLETES
UNDER BIKE/RUN AND RUN CONDITIONS

by

Janice Ann Goegan

A Thesis submitted to the Faculty of Graduate Studies through the department of Kinesiology in partial fulfilment of the requirements for the Degree of Master of Human Kinetics at the University of Windsor

Windsor, Ontario, Canada

1992
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ABSTRACT

WORK-ENERGY ANALYSIS OF RUNNING TRIATHLETES
UNDER BIKE/RUN AND RUN CONDITIONS

by

Janice Ann Goegan

Five male competitive triathletes participated in three bi-weekly testing sessions. The first week consisted of a 40 km bike ride immediately followed by a 10 km run, and each successive week consisted of a 10 km run only session. Subjects were filmed during the run portions of the workout at the intervals of 1 km, 5 km, and 9 km. High speed film data gathered at 50 fps was digitized using a 13 linked segment model. Coordinate endpoints were filtered then put into Pierrynowski’s formulae (Pierrynowski et al., 1980) for computing internal mechanical work rates.

No significant differences were found between running conditions for work, power, and energy exchange variables. Significant between condition effects occurred for stride length, velocity and total energy values for large body segments. Significant interval effects for both the bike/run and run conditions occurred between the 1 km and 5 km marks.
for the variables: $R_{Wn}$, the rate of work assuming no energy transfers; $R_{Ww}$, the rate of work assuming within segment energy transfers; $R_{Wwb}$, the rate of work assuming energy transfers within and between segments; $W_n$, the work done assuming no energy transfers; and $W_w$, work done assuming within segment energy transfers. A significant interaction effect occurred for the total energy of the trunk. There were no significant differences between the run only test and the run only retest for any of the variables.

It was concluded that the movement kinetics were not different for the run and bike/run conditions. Variations between the conditions resulted from differences between the running kinematics.
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CHAPTER I

INTRODUCTION

The triathlon is a sport which is quickly emerging and evolving. To date there is no research on the running characteristics of an athlete after a rigorous cycling bout. There is however, a wealth of research on gait characteristics. Walking and running kinetics and kinematics under conditions of fatigue, varying grades, and varying speeds have been well researched. Methodologies have been developed to calculate energy efficiencies of running; the results of which have greatly varied. Since this study will introduce a new running condition and examine it using existing research on energy efficiency equations, the methodological assumptions used to derive the equations must be examined. The next section will outline the terms to be used throughout the paper to ensure consistent vocabulary when discussing the methodologies and results of different papers and different researchers.
DEFINITION OF TERMS

The purpose of this section is to define the terms that are used in this study. The terms to be defined are: external and internal work; work efficiencies; and positive and negative work. Because the definitions of these terms vary amongst researchers it is critical to clearly define them in the context that they will be used throughout this study.

External Work

External work, often referred to as mechanical work, leads to a displacement of the centre of gravity of the body and requires some mechanical energy to be used. The energy form associated with motion is kinetic energy (Ek). The relationship between external work and kinetic energy can be illustrated as follows:

\[ W = Fs \]
\[ = mas \]
\[ \frac{2}{2} \]
substituting \( v = v_0 + 2as \)
\[ = m(v - v_0 / 2) \]
if \( v_0 = 0 \text{ m/s} \)
\[ = \frac{1}{2}mv^2 \]
\[ = Ek \text{ translational} \]
where:

\[ W = \text{external work} \]
\[ F = \text{force} \]
\[ m = \text{mass} \]
\[ a = \text{acceleration} \]
\[ s = \text{displacement} \]
\[ v = \text{velocity} \]
\[ v_0 = \text{initial velocity} \]

External work during locomotion can be determined from displacements of the centre of gravity of the body and the force applied to it as recorded by accelerometers and/or high speed film. The total external work done by the body is equal to the absolute sum of all the segmental energy states in the body such that:

\[ \text{TTL Wext} = |E_p| + |E_k| + |E_r| \]

where:

\[ E_p = \text{work against gravity (body weight \times vertical displacement of centre of gravity) known as potential energy} \]
\[ E_k = \text{work associated with speed variation in forward direction known as translational kinetic energy} \]
\[ E_r = \text{work necessary for acceleration and deceleration of limbs around their centres of mass known as rotational kinetic energy (Cavagna et al., 1963).} \]
Internal Work

Unlike external work, internal work does not lead directly to a displacement of the centre of gravity of the body. Internal work always results in a physiological cost. This physiological cost is incurred by three events: 1) by overcoming muscle viscosity; 2) by sustaining isometric muscle contractions involved in making the body rigid and in fixating the joints; and 3) by sustaining equal and opposite movements which do not contribute to the displacement of the centre of gravity of the body (Cavagna et al., 1963).

The effect of internal work manifests itself in the:

a) raising of the body against gravity (changes in $E_p$)
b) acceleration of the limbs and trunk (changes in $E_k$)
c) overcoming of internal resistances in the body
d) work done by the body on its surroundings, including the
   overcoming of external resistances (Smith, 1975).

In 1979 Winter introduced an equation for internal work which accounts for energy exchanges within each segment, energy exchanges between segments, all kinetic and potential energies, and both positive and negative work. This equation for work done assuming energy transfers both within and between segments ($W_{wb}$) will be discussed in detail later.
Work Efficiencies

Mechanical efficiency of internal work is the amount of work done per stride (i.e. the rate of work) as a proportion of the energy expended to do it. To perform the calculation, a measure of internal mechanical work, oxygen cost of performing the work, and the caloric equivalent of the metabolic substrate assumed to be the primary energy source, need to be measured (Norman et al., 1976). The denominator of the following mechanical efficiency equation includes the metabolic cost of both positive and negative work:

\[
\text{Int Mech Eff} = \frac{\text{Rate of Wwb}}{\text{(Watts)}} \frac{\text{metabolic cost}}{\text{(Watts)}}
\]

External work efficiency is calculated as being the amount of external work output per stride as a proportion of the metabolic (physiological) input (Pierrynowski et al., 1980). The numerator represents the work rate and the denominator again reflects the metabolic cost of both positive and negative work in the following equation:

\[
\text{Ext Work Eff} = \frac{\text{External work (+ve work)}}{\text{(Watts)}} \frac{\text{metabolic cost of +ve & -ve work}}{\text{(Watts)}}
\]
If the total external work done per minute and the energy cost per km do not increase with speed, this is an efficient system based on methodological assumptions (Cavagna et al., 1964).

A highly efficient running motion then, would consist of a high mechanical work output at a low physiological cost. Similarly, at a constant running speed, high efficiency would require both a low mechanical and physiological cost.

Positive and Negative Work

Both the internal mechanical efficiency equation and the external work efficiency equation account for the positive biomechanical work done. Sources of positive work are derived from energy transfer both within and between segments, movement of the body against gravity, elastic energy contributions, and concentric muscle contraction. The shortcoming of the external work efficiency equation is that it does not account for negative work. Sources of negative work are derived from movement of the body 'falling', and eccentric muscle contractions. Because negative work is aided in part by gravity, it is more efficient than positive work. Thus any external work efficiency value will be fictitiously large.
CHAPTER II

REVIEW OF LITERATURE

This review of research literature focuses on the assumptions, methodologies, and conclusive findings that have led to the formulation of energy efficiency equations.

CHANGES ASSOCIATED WITH INCREASED RUNNING SPEED

In 1938 Margaria et al., found via indirect calorimetric measurements, that the net physiological energy cost of walking increases with speed and that running is more economical than walking at speeds greater than 8.5 km/hr on a 0% grade. Refer to Figure 1. Conversely, as illustrated in Figure 2., running on a 0% grade is a linear function of speed, meaning that the net physiological energy cost per kilometre is constant and independent of speed. This latter conclusion conflicts with the hypothesis that when speed is increased, speed of muscle contraction increases, and more metabolic energy is used to overcome the viscosity of the muscle (Margaria et al., 1963).
Fig 1. Energy expenditure in kcal/kg hr as a function of speed in walking (dotted line), and running (solid line) on a treadmill on the level (0% grade), uphill (+5% grade), and downhill (-5% grade) (Margaria et al., 1963).
Fig 2. Energy expenditure in running as a function of speed in athletes (solid lines) and nonathletes (dotted line) (Margaria et al., 1963).
Earlier studies by Fenn found that subjects running at top speed exhibited similar efficiency values as did subjects climbing uphill, that is a task requiring slow muscle contractions, indicating that muscle viscosity was not the main factor limiting speed of muscle contraction (Fenn, 1930). When mechanical variables were taken into consideration running was not as mechanically efficient as walking.

Compared to walking, running was found to have a lower external work efficiency because \( E_p \) and \( E_k \) curves are in phase at all speeds therefore, \( E_p \) is not converted to \( E_k \) and thus running requires more mechanical work in order to lift the body against gravity at every step. There is also an associated increase in energy cost due to internal work because of the kinetic energies being partly absorbed by active muscles and ligaments and turned into heat. This also shows that increased internal work cost is not limited exclusively by viscosity (Margaria et al., 1963; Cavagna et al., 1964). It seems that a sizeable proportion of energy is being wasted since \( E_p \) is not converted to \( E_k \) and some proportion of \( E_k \) is being dissipated as heat.

Cavagna et al., (1964) found that as speed increases, the work done per kilometre against gravity decreases and the work done per kilometre in the forward direction increases because the angle of foot contact does not change with speed but the trajectory angle with the horizontal decreases with speed. In light of the \( E_p/E_k \) curves, this latter finding in itself could
not support the finding that the total external work done per minute does not increase with speed. In an earlier study Cavagna et al., (1963) showed that positive work at each step equals the negative work therefore the total work done at the end of the step cycle is zero. But metabolic work is not zero because both positive and negative work require muscular activity. Negative work is sustained by the gravitational force and by the inertial force so muscle energy expenditure is greater for positive work (Cavagna et al., 1963).

A new topic of research emerged to separate and subsequently calculate the relative efficiencies of positive and negative work. Further speculation queried the possibility that mechanical energy was derived from other energy sources. As early as 1930, Fenn hypothesized that elastic energy could be stored when stretching the contracted muscles (such as occurs in the phase of negative work of the step) and could then be utilized as an additional energy source during the shortening phase of the active muscular contraction (Fenn, 1930).
SERIES ELASTIC COMPONENT AND CONTRACTILE ELEMENT

In 1965, Cavagna et al., performed a benchmark study showing that positive work performed by a muscle during shortening is greater if the muscle has been stretched in the contracted state before it is allowed to shorten. The sooner the muscle is allowed to shorten after stretching, the greater the amount of positive work done. A greater positive work value implies a greater mechanical efficiency (Cavagna et al., 1965:1968).

Figure 3 shows results of an experiment where an isolated frog gastrocnemius of the length indicated in the vertical axis (18 mm), was stretched from 16 to 20 mm (dashed line, a-b-c). It was then stimulated isometrically (full line c-d) and allowed to shorten (d-a). At the end of shortening, the tension increased (a-e). The speed of stretching and shortening was 11.25 mm/sec. On the horizontal axis the tension developed is given in grams. The positive work performed was 3.94 g·cm.

Figure 4 shows experimental results of the same muscle isometrically stimulated at length 16 mm (a-b), when the maximum tension was reached, it was stretched to 20 mm (b-c). The tension subsided in approximately 5 seconds (c-d). The muscle was allowed to shorten to the original length (d-a). The positive work performed increased to 4.65 g·cm.
Fig 3. An 18 mm frog gastrocnemius isometrically stretched in the relaxed state from 16 mm to 20 mm (Cavagna et al., 1965).
Fig 4. An 18 mm frog gastrocnemius isometrically stretched in the contracted state from 16 mm to 20 mm after reaching maximum tension, shortens after a 5 s delay (Cavagna et al., 1965).
Figure 5 shows results of an experiment in which the same muscle was stimulated isometrically at length 16 mm, but when the maximum tension was reached, no delay was allowed between stretching and shortening (c-a). The positive work performed increased again to 13.04 g·cm.

The energy expenditure of the muscle during the shortening phase should be the same in the three cases since the muscle was stimulated maximally, the extent and the time of shortening being the same.

In 1968, Cavagna et al., argued that the capacity to store elastic potential energy during stretching would increase, the greater the speed of stretching and the final length reached. The greater amount of work done after stretching is not entirely accounted for by the elastic energy stored during the stretching. The contractile component itself is responsible in part for the increase. In running, the contracted extensors of the leg are stretched during the deceleration of the body which takes place when the foot makes contact with the ground and they shorten immediately after, thus giving rise to the acceleration of the body upward and forward (Penn, 1930). Potential elastic energy is stored in the undamped series elastic component and is then released during the shortening immediately following stretching. A fraction of the work done on the contracted muscle is given back as positive work during the shortening.
Fig 5. An 18 mm frog gastrocnemius isometrically stretched in the contracted state from 16 mm to 20 mm after reaching maximum tension with no delay between stretching and shortening (Cavagna et al., 1965).
The contractile component itself is able to develop a greater force during shortening after being stretched than when starting from an isometric contraction (Cavagna et al., 1968). This supports the hypothesis that the force developed isometrically at any length is greater than that finally attained after shortening to that length but less than the force at which the muscle finally settles after being stretched to that length (Abbott & Aubert, 1952). This is due to the series elastic component and the contractile component acting as a buffer when a muscle goes from a resting (flexion -'ve) to an active state (extension +'ve), and accumulating mechanical energy as the muscle tension rises. Muscle is opposed by inertial properties of the limbs or by external forces and this mechanical energy can be used in producing a final velocity (due to stored elastic potential energy) greater than that which the contractile component itself can generate. There is however, a physiological cost incurred when a muscle contracts. If and when a muscle contracts and stores mechanical energy in the series elastic component (which increases mechanical work output), the associated metabolic cost used to maintain the contracted state is not necessarily greater than the mechanical work output. This does not occur unless the extensors are prevented from relaxing (i.e. exceeding that critical interval such that elastic energy is converted to heat). External work which is due to the work performed on the muscle, requires no energy
expenditure other than that needed to sustain that specific movement after negative work is increased (Cavagna et al., 1968; Thys et al., 1972; Asmussen & Bonde-Petersen, 1974).

The rate at which muscles consume up mechanical energy during negative work and release it during positive work increases markedly with running speed. This seems reasonable since the time lag between quadricep stretching and shortening is minimized. There is also a change in potential energy during contact (i.e. the deformation of the body due to the ground reaction force) whereby potential energy decreases with speed. Compared to walking, work done against gravity even at high speeds, is greater in running. The ground reaction force increases but ground contact time decreases. What these findings suggest is that there is a quicker and more rigid 'bounce' of the body as the running speed increases (Cavagna et al., 1976).

The storage and possible utilization of mechanical energy in the muscles' elastic elements is not understood well enough to yield quantifiable relative efficiency ratios of positive and negative work in the moving human body. What can be stated is that the amount of positive work is equal to the amount of negative work done by the body but their associated efficiencies are different; negative work being more efficient than positive work. Furthermore, the sum total of positive and negative internal mechanical work output should equal the physiological cost of doing that work:
\[ +'ve \text{ work rate} -'ve \text{ work rate} \]
\[ \frac{\text{n+}}{\text{k}} + \frac{\text{n-}}{\text{k}} = \text{metabolic rate} \]

Where:

\[ \text{n+} = \text{the associated efficiency of positive work} \]
\[ \text{n-} = \text{the associated efficiency of negative work} \]
\[ \text{k} = \text{constant} \]

To complete any internal mechanical efficiency equation, it must be known that negative work is \( k \) times as efficient as positive work. There are 2 further confounding factors associated with finding 'k':

1) Mechanical energy can be dissipated into heat via passive viscosity which will transform the mechanical energy to heat at no metabolic cost.

2) Mechanical energy can also be dissipated into heat through active mechanisms in the contractile elements which carry out this function but with a metabolic cost.

To date, no study has partitioned these two elements so their relative importance is unknown. Thus the value for negative work efficiency is a fictitious value, consisting of a metabolic negative work efficiency that is theoretically infinite because it requires no metabolic cost (Pierrynowski et al., 1980).
METHODOLOGICAL VARIATIONS IN ENERGY CALCULATIONS

Mechanical power output values derived from distance running and walking studies yield data that are not replicated across studies (see Table 1). Since mechanical work rates serve as the numerator in calculating mechanical efficiency values, variation in mechanical power output values will significantly alter efficiency values.

Table 1

A comparative look at the variations in work rate values and the methods from which they were derived.

<table>
<thead>
<tr>
<th>Work Rate (W)</th>
<th>Method</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>147</td>
<td>segmental analysis^</td>
<td>Winter (1979)</td>
</tr>
<tr>
<td>166</td>
<td>segmental analysis^</td>
<td>Pierrynowski et al., (1980)</td>
</tr>
<tr>
<td>172</td>
<td>pseudowork</td>
<td>Norman et al., (1976)</td>
</tr>
<tr>
<td>343</td>
<td>centre of mass</td>
<td>Fukunaga et al., (1978)</td>
</tr>
<tr>
<td>556</td>
<td>segmental movements</td>
<td>Cavagna et al., (1977)</td>
</tr>
<tr>
<td></td>
<td>relative to centre of mass</td>
<td></td>
</tr>
<tr>
<td>931</td>
<td>pseudowork</td>
<td>Luhtanen &amp; Komi (1978)</td>
</tr>
</tbody>
</table>

N.B. ^ refers to walking studies.
The four types of analyses done to determine mechanical power output are variations of the four methods listed below:

i) Pseudowork

ii) Centre of mass alone

iii) Segmental movements relative to centre of mass

iv) Segmental analyses.

Generally these can be grouped into studies primarily concerned with; a) external work which involve movements of the body’s centre of gravity, and b) internal work which involve segmental movements to trace energy ‘flow’ throughout a gait cycle.

"When work is done on a body segment, the energy level of that segment is altered. The instantaneous energy level can be defined as the sum of the potential and kinetic (both rotational and translational) energies of the segment. These changes in energy levels can result from a variety of sources" (Williams & Cavanagh, 1983), as mentioned previously. Variations in the power calculations then, essentially result from how energy flow is interpreted as being operative in the body.
Pseudowork

Norman et al., (1976) developed the pseudowork model using a linked segment model which combined the head and neck as a single segment, the arms being considered a single segment, and the trunk, thighs, shanks and feet each being modelled as individual segments. The instantaneous work done on each segment was taken as the change in energy level from frame to frame in the motion. Absolute changes in the instantaneous energy of a segment’s potential and kinetic energies were summed together over the entire cycle:

\[
\text{TPW} = \sum_{j=1}^{n} \sum_{i=1}^{12} |\text{change } E_p| + |\text{change } E_k| + |\text{change } E_r|
\]

where:

\[
\begin{align*}
\text{TPW} &= \text{total pseudowork} \\
n &= \text{number of frames per stride} \\
12 &= \text{number of segments in model}
\end{align*}
\]

The limitation of this model is that it does not allow for energy to be transferred between segments nor does it allow for energy to be transferred between energy forms \((E_p, E_k, E_r)\). Assuming there is no energy transfer from one part of the body to another (the deceleration of a limb cannot be used to accelerate another part of the body) the internal work done is greater than if we assumed that energy can be
transferred from one part of the body to another (Cavagna et al., 1964). Each consideration taken individually overestimates work values; combined together then, they result in an even greater estimation of power.

Centre of Mass and Movement of Limbs with respect to Mass Centres

All centre of mass models assume that the sum of the individual segmental centres of gravity will represent the total body centre of gravity. These models represent the human body as a particle or a point mass. The most obvious limitation to these models is that the path of the centre of mass alone is used to calculate the internal work done by the body. Reciprocal movements such as the arm swing in running, are negated in the calculations because equally opposed motions do not lead to a displacement of the centre of mass. This leads to an underestimation of power values because reciprocal movements entail distinct changes in Ek (Smith, 1975) but are subsequently cancelled out in centre of mass calculations.

The equation $E_k = \frac{1}{2}mv^2$ is representative of the motions of a single particle with no rotation. It is hard to discern whether earlier researchers incorporated rotational kinetic energy components into their energy equations to account for lateral body movements. Failure to include rotational
energies into work equations will also lead to an underestimate of mechanical power.

In the equation above, \( E \) is the energy required to impart the speed \( v \) to the mass \( m \), and this is not related to the internal energy required in steady state running. \( E \) is spent maintaining a constant speed and can be considered as the resistance to progression. Speed in running is not constant but oscillates between the minimum and maximum values. Resistance to progression is not due to the friction of the body with the ground but mainly to the process of deceleration of the body following the heel strike on the ground at each step (Margaria et al., 1963).

The displacements of the centre of gravity of the body within the trunk were said to be important in running because of the great displacements of the limbs with respect to the trunk. The position of the centre of gravity of the whole system could be easily calculated when the position of the limbs relative to the trunk was known (Cavagna et al., 1963). Internal work due to movement of the limbs in relation to the centre of gravity specifically the \( E_k \) of the limbs in relation to the centre of gravity, was calculated from the velocity of the limbs relative to the trunk. The lower limbs contribute more than the arms to this work fraction (Cavagna et al., 1964).

If mechanical work was measured (using high speed film) from the vertical displacements of the centre of gravity of
the body and from the Ek of the limbs relative to the trunk (Fenn, 1930), this would not be sufficient to measure the work associated with displacing the centre of gravity in forward direction. This is due to the increasing forces applied to the trunk with increased speed, elucidated more in the forward direction than in the vertical direction (Smith 1975).

Segmental Analysis - The Pierrynowski Method

The Pierrynowski et. al. (1980) method models the body as a series of linked segments hinged at the joints. The underlying assumption with this method is that the energy of the centre of mass of the body will equal the sum total of all individual segmental energies. This assumes that the location of the centre of mass, the length of the radius of gyration, and the constant density of the segments are uniform throughout the population.

The work required to move any segment of the body is arrived at by summing the absolute energy changes occurring in that segment of the body. The energy in a particular segment at any one time can be calculated by summing the potential energy and the kinetic energies due to translation and rotation; as expressed by the following equation:

\[ E = mgh + \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 \]
where:

\[ E = \text{total energy of the segment} \]
\[ m = \text{the mass of the segment} \]
\[ v = \text{translational velocity of the segment relative to} \]
\[ \text{the ground} \]
\[ h = \text{vertical position of the segment relative to the} \]
\[ \text{ground} \]
\[ I = \text{segmental moment of inertia} \]
\[ W = \text{absolute angular velocity of the segment} \]

Calculating segmental energies over a number of frames of film will allow calculation of absolute energy changes for that segment over time.

The next logical step was to sum all individual segmental energy changes over time to arrive at an internal mechanical work value for the whole body. This concept was introduced by Winter et al., (1976) when an emphasis was placed on energy changes rather than absolute energy levels because an energy change indicates power flow to or from one limb to another. The equation for \( W_{wb} \) which accounts for energy transfer within and between segments is as follows:

\[ W_{wb} = \text{sum} E^{\text{seg}} + \text{sum} E^{\text{seg}+1} + \ldots + \text{sum} E^{\text{seg}n} \]

where \( \text{sum} E^{\text{seg}} \) = the sum of all energy changes for a given segment throughout all frames of film.
To calculate the amount of work done by the body assuming energy transfers only within but not between segments, all of the individual segmental energies were summed together over time, and the resulting sum of the absolute energy changes yielded $W_w$.

$$W_w = \sum E$$

where $\sum E$ = the change in the total sum of all segmental energies together from one frame to the next.

The amount of work done assuming no energy transfers within or between segments ($W_n$), previously termed pseudowork, was calculated by summing absolute changes of each energy component for each segment; then summing these totals for all segments for all frames of film.

$$W_n \text{ for one segment} = |\sum E_p| + |\sum E_k| + |\sum E_r|$$

where $\sum E_p$ = change in potential energy from one frame to the next

$\sum E_k$ = change in kinetic energy from one frame to the next

$\sum E_r$ = change in rotational energy from frame to frame

Having found $W_n$, $W_{wb}$, and $W_w$, it was finally possible to calculate the magnitudes of energy transfers within and between segments ($T_{wb}$), between segments ($T_b$) and within all segments ($T_w$) as follows:
\[ Twb = W_n - W_w \]
\[ Tb = W_w - W_wb \]
\[ Tw = Twb - Tb \]

To arrive at power values in Watts, the work values in Joules were divided by the time taken for one stride.

The Pierrynowski method (Pierrynowski et al., 1980) has taken point mass models, linked segment models and pseudowork models and has accounted for the underlying assumptions of each model to arrive at a series of work equations to accommodate for theories of energy transfer. Knowing the physiological cost (metabolic rate) of the running or walking task, the rate of work (R\(W_wb\)), and the relative efficiencies of positive and negative work, the positive and negative work efficiencies could be calculated.

There is a confounding factor limiting studies which calculate mechanical efficiency values for subjects running at predetermined treadmill speeds. That is, the energy cost of running increased rapidly as stride rate deviated from the subject’s accustomed race pace (Clarke et al., 1985). Since physiological cost is equated with internal mechanical efficiency (\(W_wb\)), efficiency values may be lower due to the increased metabolic cost incurred when running at an uncustomary pace.

Another confounding factor was the lack of validity of the relative work efficiency ratios. The most accurate data to date seem to yield a ratio of negative work at least 2.5
times as efficient as positive work in walking and an even higher ratio for running based on knee bend experiments (Asmussen & Bonde-Peterson, 1974; Thys et al., 1972) and treadmill experiments (Cavagna & Kaneko, 1977; Ito et al., 1983). Unfortunately there is no way to directly quantify the amount of stored elastic energy in the muscle during the negative work phase stretching, which is subsequently released during shortening.

To recapitulate what is known about efficiency ratio's, positive work done by the muscles is derived from: a) the chemical energy transformed by their contractile machinery and b) the mechanical energy stored in their elastic elements during a preceding phase of negative work. The approximate efficiency of the transformation of chemical energy into positive mechanical work by the muscles is about 0.25 for human walking and slightly higher for running. This means part of the positive work is being delivered free of cost by elastic elements stretched by some external force during a preceding phase of negative work (Cavagna & Kaneko, 1977). Exact values for the relative efficiencies of positive verses negative work in running cannot be directly determined. Since comparing work efficiency values between studies is futile considering the variations amongst researchers in the calculation of mechanical work rates, 'workable' efficiency values remain highly postulative.
KINEMATICS OF RUNNING

In any foot race, including the triathlon, the fastest athlete wins. This person may not necessarily be the most efficient according to the available kinetic analyses. Williams and Cavanagh (1987) looked at the relationship between distance running mechanics, running economy, and performance because to date there was little information available to link actual performance times to kinematic variables. Other researchers (Clarke et al., 1985; Adelaar, 1986; Raibert, 1986; Claremont & Hall, 1988) began quantifying the factors of different running styles which are associated with better performance.

A goal for applied biomechanical research in the area of running would be to derive a mathematical model which would account for and manipulate mechanical variables to arrive at an ideal running form. Developing mathematical models for running has been unsuccessful because of subject variation in:

a) VO2 max, VO2 submax
b) sex
c) body composition, physiological make-up
d) anatomical structure
e) running form
f) ability to conform to treadmill testing speed
g) psychological factors
Williams and Cavanagh (1983) suggest that the essential characteristics of an economical runner are not related to any predetermined set of variables but are associated with an overall combined effect from a large number of variables. They further suggest that runners will adopt specific running styles that are best suited to their anatomical and physiological make-up.

Biomechanical factors of running style have a substantial influence on energy expenditure during distance running, insofar as the extent of neurological and psychological factors are unknown (Williams and Cavanagh, 1983).

STATEMENT OF THE PROBLEM

The purpose of this study was to ascertain whether or not a triathlete’s running kinetics and kinematics change at various intervals:

a) during a straight out 10 km run
b) during a 10 km run preceded by a 40 km bike ride
c) when comparing a to b for each subject

The protocol for the chosen test format was based on the official "Olympic" race distances outlined by the international governing body for the triathlon as being a 1.5 km swim followed by a 40 km cycle followed by a 10 km run.
CHAPTER III

RESEARCH METHODOLOGY

Variables

The statistical model used was a 2 X 3 factorial design. The independent variables were the bike/run and run conditions of which there were three levels; these were the intervals at 1 km, 5 km, and 9 km. The dependent variables measured at each interval were separated into kinetic and kinematic variables.

The kinematic variables studied were stride length, time per stride, and instantaneous interval velocity. Mechanical work values were calculated at each filmed running interval from kinetic data.

The kinetic variables measured for each body segment at every interval were: Wwb, work done assuming energy transfers within and between segments; Ww, work done assuming energy transfers within segments; Wn, work done assuming no energy transfers; Twb, energy transfer within and between segments; Tw, energy transfer within segments; Tb, energy transfer between segments. Work rates were calculated for each work value; RWwb, RWw, and RWn and transfer rates were calculated for each transfer value; RTwb, RTw, and RTb.
Limitations

The following limitations were acknowledged and measures were taken to eliminate or minimize their effects:

1) None of the subjects had previously participated in scientific experiments. To avoid performance alterations in front of the camera, the athletes were not told which intervals were being filmed.

2) To avoid overlapping inside the filming area, a chute was erected on the corner of the track. The subjects were instructed not to pass after exiting the chute. Running order was maintained throughout the straight of the track.

3) Triathletes train for two or three events daily. To minimize variations in fatigue levels amongst the subjects, they were asked not to train that day prior to the testing session.

4) A water station was set up to allow the subjects to ingest fluids as they normally would while competing.

5) Only competitive athletes were chosen as subjects ensuring that running 10 km after a 40 km bike ride was not a novel task.

Delimitations

As a consequence of using a small sample size with expected variations in running and cycling ability, a delimitation of
this study is an inability to generalize results to the neophyte or elite triathlon population. The researcher also chose to alter triathlon cycling protocol to ensure rider safety.

Triathlon cycling courses forbid drafting. The courses are well marked, supervised at every point, and use traffic control measures. Because the resources to set up a regulation course were beyond the means of the researcher, no restrictions regarding drafting were enforced, thereby allowing the subjects to cycle as a visible group on the roads.

Regardless of whether or not drafting techniques were employed by the athletes, peak performances were assumed to have resulted.

Subjects

Five competitive male triathletes ranging in age from 23 to 33 years composed the subject pool. Each subject participated in three testing periods conducted over three nonconsecutive weeks. The format was as follows:

Week #1  40 km bike followed by a 10 km run
Week #2  10 km run
Week #3  10 km run
Data Collection

i) Film

Each subject was filmed for two full running cycles during the 10 km runs at the completion of 1 km, 5 km, and the 9 km. Filming was done using a Locam camera operating at 50 fps. The camera was set up perpendicular to the running path of the subjects. The subjects ran ten laps around a 1 km square circuit course. The camera was positioned at approximately the midpoint of one leg of the circuit such that the athletes were not entering nor leaving a corner during filming.

A meter stick was placed in the filming area following each data collection session to be used as a scale factor during the digitizing process.

Data Analysis

i) Film

The high speed film was digitized using an Altek 30 digitizer linked on-line to an Apple computer. Data from the joint markings were collected for 1 stride that is, from heel strike of the left foot to heel strike less one frame of the right foot. Segmental end point data were filtered at a cutoff frequency of 5 Hz through use of a Butterworth fourth-order low pass digital filter. Smoothed data were used in subsequent calculations of kinematic and kinetic variables.
ii) Method

Work, work rate and energy transfer values were calculated using the Pierrynowski method (Pierrynowski et al., 1980). This method was discussed in detail on pages 19 through 24.

This method was chosen because it is mechanically accurate, has physiological parameters, and provides useful diagnostics of motion kinetics (Norman et al., 1985). Centre of mass models were not used because modelling the body as a particle or point mass negates reciprocal movements of the body such as the swinging of the arms and are therefore mechanically inaccurate for a running analysis. Models using limb movements relative to the trunk cannot measure work associated with displacing the centre of gravity in the forward direction which occurred in the gait motion of this study. These models too, are mechanically inaccurate for studying running motion.

Ideally it would be desirable to calculate mechanical work done from force/length change relationships for each individual muscle during running and to partition this work done into positive and negative components. Although this has been done on individual muscle fibres as previously discussed (Cavagna et al., 1965:1968), this is presently beyond present scientific capabilities for whole body motion.

The next closest approximation of mechanical work output would be from a force plate/film analysis to yield force moment/displacement data. Using one 45 square centimetre
force plate for a field study where stride lengths are in excess of 1.5 metres would not be capable of collecting data at every trial. Until larger force plates are available, this method is not practical for running studies.

iii) Statistics

General linear models were generated from a SAS statistical package. 2 X 3 repeated measures ANOVA’s were done on each of the 15 dependent variables to test for a) differences between each of the three running intervals within each test condition; and b) to compare differences between the independent variables that is, the run and bike/run conditions at each interval. Studentized Newman-Keuls post-hoc tests determined where differences existed. Data collected from both 10 km only runs (Week #2 and Week #3) were used to test subject reliability. A dependent samples t-test was completed to assess test-retest reliability. Mean difference scores were obtained where df=4.
CHAPTER IV

RESULTS AND DISCUSSION

Table 2 and Table 3 show the rates of internal mechanical work and the rates of energy transfer. Statistically significant interval effects (p < 0.05) were evidenced for the variables Wn, RWN, Ww, RWw, and RWwb. Studentized Newman Keuls post hoc analysis with alpha < 0.05, revealed that in each case these differences occurred between the first and second trials that is, between the 1 km and 5 km intervals. Means comparisons for the set of dependent variables showed a significant decreasing trend from the 1 km to the 5 km interval followed in each case by a nonsignificant increasing trend from the 5 km to the 9 km mark. No significant differences existed for the variables Tb, RTb, Tb, RTb, Twb, RTwb, and Wwb. Refer to Appendix 1, Table A1 and Table A2 for raw data values.

Total energy values for the arm, forearm, leg, thigh, and trunk segments had significant F-ratios at p < 0.05 for the independent variables. The post hoc analysis with alpha < 0.05, showed that when comparing the bike/run condition to the run condition, the between subject effects occurred at the 1 km, 5 km, and 9 km intervals. Total energy values were greater at every interval on the run only trial. Refer to Table 5 and Table 6.

The trunk segment was the only segment to elicit an
interval x condition interaction effect. Within subject effects for the total energy of the trunk significantly increased between the 1 km and 5 km interval and between the 1 km and the 9 km interval using post hoc alphas < 0.05. For raw data values refer to Appendix 1, Table A4 and Table A5. Work rate values were compared to those of other studies using segmental analysis for walking (Winter, 1979 and Pierrynowski at al., 1980). Data gathered were approximately ten times greater than the results found in walking studies. These values appear to be valid when considering the effects of gravity on the falling body during the flight phase of running.

The kinematic variables stride length and running velocity had significant F-ratios at p < 0.05 for between condition effects. For stride length, differences between the bike/run and run conditions occurred at the second and third trial (the 5 km and 9 km interval) using alpha < 0.05. Refer to Figure 6. Differences in velocities occurred at the 1 km, 5 km, and 9 km intervals using post hoc alphas of < 0.05. Refer to Figure 7. Where significant differences occurred for stride length and velocity data, means were greater for the run only trial. Although the means for the time taken per stride decreased slightly during the run only trial (see Figure 8), no significant differences occurred on time per stride data. Refer to Table 7 for means summary or to Table A6 in Appendix 1, for raw data points.
Dependent samples t-tests were used to differentiate between means on the run only test and the run only retest using the kinetic variables Tb, RTb, TW, RTw, Twb, RTwb, Wn, RWN, Ww, RWw, Wwb, and RWwb. In all cases no significant differences between means occurred at \( p < 0.05 \). Retest means summary appear in Table 4 with raw data scores appearing in Appendix 1, Table A3. For critical F-ratios and t values refer to Appendix 1, Table A7. A Spearman rank-order correlation for the subjects' finishing positions had a result of \( r = 1.0 \) with \( N = 5 \) at the 95% confidence level.
Table 2

Rates of internal mechanical work
and rates of energy transfer
for the bike/run condition
(N = 5)

<table>
<thead>
<tr>
<th>Trial</th>
<th>*RWwb (W)</th>
<th>*RWw (W)</th>
<th>*RWm (W)</th>
<th>RTw (W)</th>
<th>RTb (W)</th>
<th>RTwb (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>707.9</td>
<td>2234.6</td>
<td>2844.5</td>
<td>610.0</td>
<td>1526.7</td>
<td>2136.7</td>
</tr>
<tr>
<td>S</td>
<td>627.2</td>
<td>383.9</td>
<td>877.6</td>
<td>645.7</td>
<td>641.0</td>
<td>1012.6</td>
</tr>
<tr>
<td>T2</td>
<td>361.8</td>
<td>1732.3</td>
<td>2068.7</td>
<td>336.4</td>
<td>1381.8</td>
<td>1718.2</td>
</tr>
<tr>
<td>S</td>
<td>306.6</td>
<td>335.1</td>
<td>376.7</td>
<td>186.7</td>
<td>316.0</td>
<td>399.1</td>
</tr>
<tr>
<td>T3</td>
<td>679.1</td>
<td>2025.7</td>
<td>2426.0</td>
<td>400.3</td>
<td>1346.6</td>
<td>1746.9</td>
</tr>
<tr>
<td>S</td>
<td>512.6</td>
<td>672.4</td>
<td>693.7</td>
<td>94.7</td>
<td>266.3</td>
<td>308.0</td>
</tr>
</tbody>
</table>

F-ratio 3.94 6.53 5.53 0.52 0.57 0.8

* Statistically significant differences between trials at p < 0.05.
### Table 3
Rates of internal mechanical work and rates of energy transfer for the run condition (N = 5)

<table>
<thead>
<tr>
<th>Trial</th>
<th>( \bar{X} ) RWwb (W)</th>
<th>( \bar{X} ) RWw (W)</th>
<th>( \bar{X} ) RWN (W)</th>
<th>RTw (W)</th>
<th>RTb (W)</th>
<th>RTwb (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>669.0</td>
<td>2401.8</td>
<td>2729.2</td>
<td>327.4</td>
<td>1732.8</td>
<td>2060.2</td>
</tr>
<tr>
<td>S</td>
<td>418.6</td>
<td>480.1</td>
<td>519.4</td>
<td>53.1</td>
<td>486.4</td>
<td>502.7</td>
</tr>
<tr>
<td>T2</td>
<td>190.3</td>
<td>1747.6</td>
<td>2091.6</td>
<td>344.0</td>
<td>1557.3</td>
<td>1901.3</td>
</tr>
<tr>
<td>S</td>
<td>120.8</td>
<td>355.8</td>
<td>412.5</td>
<td>80.8</td>
<td>293.9</td>
<td>358.7</td>
</tr>
<tr>
<td>T3</td>
<td>377.0</td>
<td>1955.3</td>
<td>2401.5</td>
<td>446.1</td>
<td>1586.3</td>
<td>2024.5</td>
</tr>
<tr>
<td>S</td>
<td>303.1</td>
<td>341.7</td>
<td>391.2</td>
<td>217.7</td>
<td>172.1</td>
<td>139.4</td>
</tr>
</tbody>
</table>

| F-ratio | 3.94 | 6.53 | 5.53 | 0.52 | 0.57 | 0.8 |

* Statistically significant differences between trials at \( p < 0.05 \).
Table 4
Rates of internal mechanical work
and rates of energy transfer
for the run retest condition
(N = 5)

<table>
<thead>
<tr>
<th>Trial</th>
<th>RWwb (W)</th>
<th>RWw (W)</th>
<th>RWh (W)</th>
<th>RTw (W)</th>
<th>RTb (W)</th>
<th>RTwb (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>666.6</td>
<td>2410.5</td>
<td>2733.9</td>
<td>325.4</td>
<td>1737.0</td>
<td>2062.8</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>422.2</td>
<td>493.5</td>
<td>519.3</td>
<td>53.8</td>
<td>521.6</td>
<td>499.8</td>
</tr>
<tr>
<td>F</td>
<td>1.02</td>
<td>1.06</td>
<td>1.00</td>
<td>1.03</td>
<td>1.15</td>
<td>1.01</td>
</tr>
<tr>
<td>T2</td>
<td>186.5</td>
<td>1704.9</td>
<td>2093.3</td>
<td>391.4</td>
<td>1516.0</td>
<td>1907.3</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>118.8</td>
<td>331.2</td>
<td>411.5</td>
<td>132.4</td>
<td>279.6</td>
<td>348.5</td>
</tr>
<tr>
<td>F</td>
<td>1.03</td>
<td>1.15</td>
<td>1.00</td>
<td>2.68</td>
<td>1.10</td>
<td>1.06</td>
</tr>
<tr>
<td>T3</td>
<td>418.3</td>
<td>1932.1</td>
<td>2453.5</td>
<td>431.4</td>
<td>1513.7</td>
<td>2003.2</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>271.3</td>
<td>370.2</td>
<td>422.1</td>
<td>255.5</td>
<td>241.1</td>
<td>170.9</td>
</tr>
<tr>
<td>F</td>
<td>1.25</td>
<td>1.17</td>
<td>1.16</td>
<td>1.38</td>
<td>1.96</td>
<td>1.50</td>
</tr>
</tbody>
</table>
Table 5
Mean total energy values for body segments
on the bike/run condition
(N = 5)

<table>
<thead>
<tr>
<th>Trial</th>
<th>*</th>
<th>FORBARM</th>
<th>*</th>
<th>LEG</th>
<th>**</th>
<th>THIGH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ARM</td>
<td>(J)</td>
<td></td>
<td></td>
<td>(J)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(J)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>X</td>
<td>108.5</td>
<td>61.2</td>
<td>186.9</td>
<td>2225.6</td>
<td>371.3</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>5.2</td>
<td>2.8</td>
<td>21.1</td>
<td>120.0</td>
<td>2.9</td>
</tr>
<tr>
<td>T2</td>
<td>X</td>
<td>115.4</td>
<td>63.0</td>
<td>200.5</td>
<td>2440.1</td>
<td>402.4</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>11.1</td>
<td>5.1</td>
<td>30.0</td>
<td>210.9</td>
<td>40.4</td>
</tr>
<tr>
<td>T3</td>
<td>X</td>
<td>115.5</td>
<td>65.4</td>
<td>191.8</td>
<td>2447.0</td>
<td>395.1</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>10.3</td>
<td>6.1</td>
<td>29.4</td>
<td>249.8</td>
<td>47.5</td>
</tr>
<tr>
<td></td>
<td>F-ratio</td>
<td>109.31</td>
<td>117.02</td>
<td>48.24</td>
<td>95.12</td>
<td>91.09</td>
</tr>
</tbody>
</table>

* Statistically significant differences between conditions at p < 0.05.

** Statistically significant interval effect at p < 0.05.
F = 8.15 with 2,16 df.

** Statistically significant interaction effect at p < 0.05.
F = 5.12 with 2,16 df.
Table 6
Mean total energy values for body segments on the run condition
(N = 5)

<table>
<thead>
<tr>
<th>Trial</th>
<th>ARM (J)</th>
<th>FOREARM (J)</th>
<th>LEG (J)</th>
<th>TRUNK (J)</th>
<th>THIGH (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>$\bar{x}$ 180.8</td>
<td>101.2</td>
<td>300.2</td>
<td>3668.1</td>
<td>615.1</td>
</tr>
<tr>
<td></td>
<td>S 10.2</td>
<td>5.6</td>
<td>23.4</td>
<td>212.6</td>
<td>37.4</td>
</tr>
<tr>
<td>T2</td>
<td>$\bar{x}$ 179.6</td>
<td>101.3</td>
<td>297.1</td>
<td>3686.2</td>
<td>610.0</td>
</tr>
<tr>
<td></td>
<td>S 12.7</td>
<td>8.2</td>
<td>26.8</td>
<td>264.9</td>
<td>44.4</td>
</tr>
<tr>
<td>T3</td>
<td>$\bar{x}$ 179.8</td>
<td>100.7</td>
<td>306.0</td>
<td>3699.9</td>
<td>624.4</td>
</tr>
<tr>
<td></td>
<td>S 12.4</td>
<td>6.4</td>
<td>23.2</td>
<td>244.5</td>
<td>41.0</td>
</tr>
<tr>
<td>F-ratio</td>
<td>109.31</td>
<td>117.02</td>
<td>48.24</td>
<td>95.12</td>
<td>91.09</td>
</tr>
</tbody>
</table>

* Statistically significant differences between conditions at p < 0.05.
** Statistically significant interval effect at p < 0.05.
  F = 8.15 with 2,16 df.
** Statistically significant interaction effect at p < 0.05.
  F = 5.12 with 2,16 df.
Figure 6. Stride lengths at 1 km, 5 km, and 9 km intervals for the 1) bike/run condition and the 2) run only condition.
Figure 7. Instantaneous velocities at the 1 km, 5 km, and 9 km intervals for the 1) bike/run condition and the 2) run only condition.
Figure 8. Stride rate at the 1 km, 5 km, and 9 km intervals for the 1) bike/run condition and the 2) run only condition.
Table 7
Stride length, time per stride, and velocity values for bike/run and run conditions
(N = 5)

<table>
<thead>
<tr>
<th>Trial</th>
<th>BIKE/RUN</th>
<th></th>
<th>RUN</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>* SL</td>
<td>* TPS</td>
<td>* V</td>
<td>* SL</td>
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<tr>
<td></td>
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<td>(s)</td>
<td>(m/s)</td>
<td>(m)</td>
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</table>

F-ratio 15.43 1.10 38.4

* Statistically significant differences between conditions at p < 0.05.
Interval Effects

At the onset of the running bouts, values for work done (except for Wwb) and the rate of working, or power output, were relatively high compared to the later stages of the run. Between the 1 km and 5 km mark there was a significant decrease in work and work rate values (except for Wwb) and there were no significant changes in energy transfer, stride length, time per stride, velocity and except for the trunk, total energy values for the larger body segments.

\( W_n \) and \( W_w \) decreased significantly within subjects from the 1 km to the 5 km point but Wwb did not decrease significantly. This affected the energy transfer values where no significant differences occurred. Since no additional work was being done within and between segments, no increases in energy transfers took place.

\( RW_{wb} \) decreased from the 1 km to 5 km marks within each condition. Since the work done within and between segments showed no significant decreases during the same period, the time taken to complete the work increased. Increasing trends in the energy level of the trunk across intervals, with significant increases from the first to the second interval, should incite a corresponding increase in energy transfer within the trunk segment and between other segments. There was however, no net change of energy transfer for the body. The increased energy of the trunk alone did not affect \( W_{wb} \) nor
did it subsequently affect energy transference values.

The total energy of the trunk increased because the potential energy increased. There was a decreased ability to convert the potential energy of the trunk due to its position above the ground to kinetic translational energy. The diminished capacity to transfer energy between forms may have resulted in less of a rigid 'bounce' of the body upon foot contact (Cavagna et al., 1976) thereby increasing ground contact time. Thus, power decreased because it took longer to complete the work. Furthermore, a portion of the negative work acquired while the body fell was not given back as positive work during recoil after the body hit the ground. This diminished the ability of the body to raise the centre of gravity of the body upward and forward after heel strike.

Between the 5 km and 9 km marks, no significant increases occurred in total energy of the trunk, but total energy of the trunk did increase significantly between the 1 km and 9 km marks. This indicates a small nonsignificant increase in total energy of the trunk between the 5 km and 9 km interval. There were no further statistically significant decrements in work or work rate values. Because the trunk continued to produce higher total energy values, this time without associated changes in work or power output, the potential and kinetic energies were not being exchanged between forms and the $E_p$ and $E_k$ curves continued to become more in phase. Either more negative work was being converted to positive work
during recoil or less energy was being dissipated as heat compared to the first interval. Also, since there were no significant transfer value effects between intervals and the total energy of the trunk increased throughout the run, metabolic inputs were not effectively utilized.

Without being able to effectively increase energy exchanges within and between segments or the rate at which energy is exchanged within and between segments when given an increase in the total energy of any given segment or segments, the movement is mechanically inefficient. An efficient movement pattern would show increased energy exchanges within and between segments when provided with increases in total segmental energies at a given metabolic rate. This did not occur over the course of this study.

Condition Effects

Total energy created by the large body segments during the bike/run condition was significantly decreased at every interval compared to the run only condition. Work, power and energy exchange values showed no significant changes between the bike/run and run conditions. Velocity values also decreased over all intervals from the run to the bike/run condition. To state that the effect of decreasing total energy during the bike/run condition manifests itself in the decreased horizontal velocities at every tested interval would
be erroneous since no cause and effect relationships were tested.

Total segmental energies were significantly reduced during the bike/run trial at all intervals, but the work and power values did not change. Mean total energy decreases in the thigh comparing the run condition to the bike/run condition for the 1 km, 5 km and 9 km intervals are 615.1 J - 371.3 J, 610.0 J - 402.4 J, and 624.4 J - 395.1 J, respectively. These decreases range from 60 to 66 per cent of the total energy available during the run condition. The same percentage range prevails for decreases in total energy of the trunk. Values for the run condition and the bike/run condition at the 1 km, 5 km, and 9 km intervals were as follows: 3668.1 J - 2225.6 J, 3686.2 J - 2440.1 J, and 3699.9 J - 2446.9 J.

This indicates that the potential and kinetic energies for all the large body segments were not effectively exchanged between energy forms. Energy was not being translated to mechanical work and this was magnified during the run only condition where more total energy was recorded. If metabolic cost was constant or could not have been increased more than it was at the time of the testing sessions due to maximal efforts, and knowing that energy transfers did not show condition effects, it was concluded that increases in total segmental energies did not affect work and power values across conditions.
During the 40 km bike portion of the testing session, subjects were predominantly using the quadriceps muscle group as they pedalled in a cyclic motion. The muscles of the trunk were used as postural muscles, maintaining the body position on the bike. These muscles were mainly undergoing isometric muscle contractions, sustaining the thighs as they pushed up and down on the pedals and the arms as they pushed down on the aerodynamic handlebars. As the athletes began to run, less total energy was available to these large segments due to energy output expended on the bike. Because the trunk was fatigued, hip flexion was not well supported during the stance phase as the thigh drove upward. This impaired the conversion of potential energy to kinetic energy within and between the large body segments as the body fell. Quadriceps fatigue decreased leg extension at foot contact which again limited the conversion of Ek to Ep (the rigid bounce of the body). As the run progressed, more energy needed to be present in the trunk to support the raising of the leg during the stance and flight phases of the running stride. Tightness of the gastroc-soleus complex from the bike exertion could alter the way in which the body moves over its centre of gravity during the stance phase of running. This could explain the decreased ability to transfer a portion of the negative work gained from the flight phase to positive work during recoil.
Kinetiatics

The kinematic data showed that velocity was significantly lower at all intervals for the bike/run condition. Time per stride did not show statistically significant changes when subjected to the independent variables. Stride length was significantly shorter during the bike/run condition when compared to the run condition at the 5 km and 9 km trials. Velocity decreased for the bike/run trial at the 5 km and 9 km intervals because of the associated decrease in stride length.

The velocity at the 1 km interval yielded a statistically significant lower velocity for the bike/run condition. There were however, no significant decreases in stride length between the bike/run condition and the run condition at the 1 km trial due to high subject variances. There was a non-significant increase in stride rate between the 1 km and 5 km trials during the run.

The mean velocity data showed no significant interval effects. The mean bike/run velocity at the 1 km and 5 km interval was 4.3 m/s or a 38:42 minute 10 km pace time. The 9 km interval time was 4.2 m/s or a 39:42 minute 10 km pace time. The mean 1 km, 5 km, and 9 km lap velocities for the run only session were 5.6 m/s, 6.4 m/s, and 6.8 m/s respectively. Although they were not statistically different, the translated difference for the run only interval times as 10 km pace times is as follows: 5.6 m/s pace (approximately
5 minute miles) is a 30 minute 10 km, 6.4 m/s pace (approximately 4:20 minute miles) is a 26 minute 10 km, and 6.8 m/s pace (approximately 4 minute miles) is a 24.5 minute 10 km. These differences in pace times become important to the racing athlete even though for the purposes of this research they were not considered to be statistically significant.

Notwithstanding the latter two paragraphs, although there was no significant interaction effect for velocity, the graphic representation of the velocity data for the bike/run and run conditions suggest that an interaction effect exists albeit insignificant.

The instantaneous velocity data gathered in this study was compared to Olympic 10 km times and to Triathlon World Cup 10 km times to check for validity. The winning Olympic 10 km run times are approximately 26 minutes. Instantaneous velocity data gathered at the 5 km mark of the run only session was approximately translated to a 26 minute 10 km pace time. Since the 1 km mark pace time was greater than a 30 minute 10 km pace time, the athletes were not running consistently at an Olympic pace. This indicates that these athletes were running a pace indicative of a competitive runner at the provincial/national level of competition.

Winning 10 km event times during World Cup triathlon races on a flat course are approximately 33 minutes. Data gathered from the bike/run condition instantaneous velocity
ranged from 38:42 to 39:42 10 km times. These are respectable and finishing times for a competitive triathlete at the provincial/national level. Running time data collected in this study is slightly less than world class times and is indicative of competing athletes at the provincial/national level and is therefore valid for use under the parameters of this study.
CHAPTER V

SUMMARY AND CONCLUSION

Running Kinetics

This work - energy analysis of the running mechanics of triathletes showed how work, work rates and energy exchanges were affected by interval effects at 1 km, 5 km, and 9km intervals for both a 10 km run only condition and a 10 km run condition immediately preceded by a 40 km bike ride.

Significant decreases in power (RWWb) occurred in both the run and bike/run condition as the athlete progressed from the 1 km to the 5 km mark. This, accompanied by significant increases in the total energy of the trunk and no significant changes in work (WWb), energy transfer (Twb), or the rate of transfer (RTwb), was indicative of an inefficient movement pattern. The trunk was used to support the hip as it was used to maintain the stride length and the recovery height of the free leg. Since there were no energy transfers between segments nor between energy forms, the kinetic energy or work done by the body did not change. Because the potential and kinetic energy curves for the hip were in phase, there was less of a 'rigid bounce' upon foot contact. The increased contact time where potential energy was wasted and not converted to kinetic energy produced less power per push off
and required more metabolic input to achieve the same energy level of the hip during the recovery phase for the next stride. Additional research is needed to corroborate these findings. Specific measurements of ground contact times and specific joint torques are required.

The total energy of the trunk increased from the 1 km to the 9 km trials. There were no statistically significant changes in Wwb, RWWb, or transfer values. It was concluded that the athletes were not effectively utilizing metabolic inputs. Gas collection techniques would be useful to determine to what extent changes in work and energy exchange values were accompanied by changes in physiological cost. Future studies using gas analyses would also expand the present study to yield efficiency values.

Because there was a non significant but increasing trend in work and power values from the 5 km to the 9 km mark, future studies should partition the intervals to include a final 10 km mark to investigate changes at the final portion of the run.

The segmental energy analysis for the large body segments provided a total energy profile for the acting segments during the different running conditions. Findings from this study showed that total energy of the large segments was significantly decreased at all intervals for the bike/run condition. Further investigation of joint torques and segmental power output would help to clarify specific
mechanical changes associated with fatigue. Joint torques could also be examined to determine the effects on stride length and total segmental energy.

Running Kinematics

The kinematic assessment of velocity variables supplied information as to how the athletes were able to manipulate stride length and stride rate between each run condition. The stride length decreased significantly during the bike/run condition and this in turn caused velocity to significantly decrease since stride rate was unaffected by condition effects. The subjects ran slower after coming off the bike due to the trunk and quadricep fatigue which resulted in abbreviated stride lengths.

Bike/run condition velocities were significantly lower at the 1 km interval but it was not determined whether stride rate or stride length was the underlying factor because neither variable yielded significant differences between conditions. Future research should include a bike/run condition retest to ensure a homogenous subject group for the stride length variable. Another research alternative would incorporate runners as the control group (to complete only the run condition) to be compared to the triathletes on the bike/run condition. This may also clarify whether or not triathletes exhibit similar running patterns as runners.
There may be a critical time factor wherein running mechanics deteriorate. It is possible that bike/run condition running which takes approximately 10 minutes longer than the run only condition to complete 10 km, is independent of the effects of the bike ride and is related to the time taken for that activity. Further studies could have the triathletes complete a 40 minute timed run (the approximate time taken to run 10 km after a 40 km bike ride) to compare kinetic and kinematic values to the original bike/run and run data.

Finally, although the change in velocity between intervals was not statistically significant, the run only condition data showed that the subjects’ velocity was greater at each passing interval. The bike/run data showed that velocity decreased insignificantly at the 9 km trial compared to the 1 km and 5 km trials. It was concluded that albeit insignificant statistically, triathletes were able to run negative splits during the run only condition but could not do this on the bike/run condition. Again, future research in this area should include studying kinematic variables: maximum vertical displacement of the body; ground contact time; maximum extension of the thigh & leg; and work & power values for the arms in isolation; to attempt to describe these differences in movement patterns.

Keeping in mind the methodological limitations of this study, results show that work, work rates, and energy exchange values are statistically unaffected by running condition
although total segmental energies and velocities due to stride lengths are significantly decreased during the bike/run trials. For the competitive triathlete, biomechanical advice that can be given from this study to improve running kinematics in a triathlon would be to increase stride length without altering stride rate. The results of the kinetic assessment gives insight as to how the forces within the body can be manipulated to improve overt performance.

As long as the total energy for the large body segments remain high, velocities will be higher. However, the total energy available for the large body segments are significantly less at every interval for the bike/run condition. In light of this fact, the total energy of the trunk becomes important. As the total energy of the trunk increased from the 1 km to the 5 km mark, stride rate and velocity increased but the power and stride length decreased. As the total energy of the trunk decreased from the 5 km to the 9 km marks so too did stride rate data. During the same interval, power and stride length increased. Because power is proportional to force and velocity, and power and velocity are inversely proportional when the total energy of the trunk is introduced, power becomes proportional to the applied force. The moment of force or torque of any segment is proportional to not only the force applied by that segment but by the distance from its rotational axis. As the total energy of the trunk increases, joint torques decrease because of decreased force application
(producing decreased power values) and decreased dispersion of mass around joint centres viewed as abbreviated strides and exhibited in the decreased stride length data.

Total energy of the trunk therefore, has a positive relationship with speed and a negative relationship with joint torques. This becomes an optimization task for the athlete. The goal is to decrease the total energy of the trunk such that joint torques can be effectively utilized to increase stride length during the bike/run condition without decreasing stride rate.
REFERENCES


APPENDIX
Table A1
Rates of internal mechanical work
and rates of energy transfer
for the bike/run condition
(N = 5)

<table>
<thead>
<tr>
<th>S/Trial</th>
<th>RWwb (W)</th>
<th>RWw (W)</th>
<th>RWnd (W)</th>
<th>RTw (W)</th>
<th>RTb (W)</th>
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Table A2

Rates of internal mechanical work
and rates of energy transfer
for the run condition
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Table A3

Rates of internal mechanical work
and rates of energy transfer
for the run retest condition

(N = 5)

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<td>352.8</td>
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Table A4

Mean total energy values for body segments on the bike/run condition

(N = 5)

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<tr>
<th>S/Trial</th>
<th>ARM (J)</th>
<th>FOREARM (J)</th>
<th>LEG (J)</th>
<th>TRUNK (J)</th>
<th>THIGH (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 T1</td>
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<td>397.0</td>
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<td>249.4</td>
<td>2669.3</td>
<td>461.8</td>
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<td>70.1</td>
<td>230.1</td>
<td>2713.9</td>
<td>457.3</td>
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<td>60.0</td>
<td>194.3</td>
<td>2261.7</td>
<td>382.4</td>
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<td>60.4</td>
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<td>2389.3</td>
<td>390.0</td>
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<td>360.7</td>
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<td>381.2</td>
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Table A5

Mean total energy values for body segments on the run condition
(N = 5)

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<th>ARM (J)</th>
<th>FOREARM (J)</th>
<th>LEG (J)</th>
<th>TRUNK (J)</th>
<th>THIGH (J)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>660.0</td>
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<td>3954.3</td>
<td>665.1</td>
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<td>580.7</td>
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<td>581.8</td>
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<td>307.1</td>
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<td>628.3</td>
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<td>108.5</td>
<td>314.6</td>
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<td>108.3</td>
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<td>625.5</td>
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<td>103.0</td>
<td>296.0</td>
<td>3769.8</td>
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<td>299.2</td>
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<td>94.6</td>
<td>273.5</td>
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<td>570.2</td>
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</table>
Table A6

Stride length, time per stride, and velocity values for bike/run and run conditions

(N = 5)

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<thead>
<tr>
<th>S/Trial</th>
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<th>RUN</th>
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<tbody>
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<td></td>
<td>SL (m)</td>
<td>TPS (s)</td>
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</tr>
<tr>
<td>S1 T2</td>
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<td>0.4</td>
</tr>
<tr>
<td>S1 T3</td>
<td>1.5</td>
<td>0.32</td>
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<tr>
<td>S2 T1</td>
<td>1.53</td>
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<tr>
<td>S2 T2</td>
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<tr>
<td>S2 T3</td>
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<tr>
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</tr>
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Table A7

T-test procedure on run conditions
for the rates of internal mechanical work
and rates of energy transfer
(df = 4)

<table>
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<th>Trial</th>
<th>RWwb</th>
<th>RWw</th>
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<th>RTw</th>
<th>RTb</th>
<th>RTwb</th>
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<td>1.06</td>
<td>1.00</td>
<td>1.03</td>
<td>1.15</td>
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<tr>
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<td>0.9998</td>
<td>0.9797</td>
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<tr>
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<td>F</td>
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<td>1.15</td>
<td>1.00</td>
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<tr>
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<td>F</td>
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