COMPARISON OF METHODS FOR CALCULATING INTERNAL WORK OF ELITE RUNNING

by

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ABSTRACT

There are two basic models that are used to calculate the internal work involved in movement. The first, an energy-based model, calculates the changes in the energy of the segments. There are many variations of this model but Aleshinsky (1986) has shown that this approach lacks mathematical validity. The other, a power-based model, integrates the joint powers to find work. A modified power model (using absolute values) was shown by Aleshinsky (1986) to be mathematically valid but has only been used in two studies (Chapman et al., 1987; Caldwell and Forrester, 1992) each having only one subject. A version of this model was used in this study and was termed the absolute power method. For comparison purposes a modified version of the energy approach, called the absolute work method, was used. The internal work was then normalized for body mass and running velocity to obtain the "internal biomechanical cost" (IBC). The IBCs of normal running for four elite male and four elite female runners were compared to their IBCs of four inefficient running styles.

The absolute power method was able to detect that the inefficient runs produced significantly higher internal work than normal running in 30 out of 32 cases (94%). Absolute work (the energy approach) could detect the inefficient runs in only 15 out of 32 cases (46%). As well, the absolute work approach was shown to be more variable and less reliable than the absolute power approach. The absolute power method also proved to be a useful tool for examining the work performed at each joint during a movement, thereby providing insight into where significant inefficiencies occur.

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INTRODUCTION

One of the biggest challenges facing the scientific community is to be able to quantitatively determine what aspects of human locomotor activity are inefficient. Although oxygen uptake can be used to determine physiological cost, this does not give insight into the mechanical differences that may exist. For example, for runner "A" with a lower cardiac capacity (MVO_2) to win a race against an otherwise equally matched competitor, runner "B", A's running style must be more mechanically efficient. To determine the mechanical differences in style, we must know how much internal work is being done by the runner. There have been many different mathematical models put forward to calculate internal mechanical cost (i.e. Pierrynowski et al., 1980; Williams and Cavanagh, 1983) but no "best" model has been found (Williams, 1985). It must be understood that because of the incredible complexity involved in human movement, all models are oversimplifications of reality and none are capable of directly measuring internal cost. Most of these models use the traditional approach of examining changes in segment energies to estimate mechanical cost. A different approach is to use the integral of the joint powers to find mechanical cost. In this study a modified version of the power model and a traditional energy model were used to calculate the work for normal running and running that was intentionally modified to be inefficient. The purpose was to see which model would be better able to detect the mechanically inefficient running styles.

External work is relatively easy to measure, but can lead to what has been termed the "zero work paradox" (Aleshinsky, 1986). Opposite motions produce equal but opposite work values which cancel each other out in the calculation of total external work done. For example running on a level treadmill or pedaling a bicycle ergometer with no resistance produce zero external work. Many researchers ignore this paradox and simply use testing situations in which it doesn't occur. With external work measures there is also the difficulty of distinguishing between efficient and inefficient motion. For example, if a person were biking against a given resistance at a set speed the amount of work calculated would be the same regardless of other extraneous movements they might be making (i.e., arm swinging).

In an attempt to eliminate the zero work paradox Norman et al. (1976) developed the "pseudowork" equation in which the **absolute values** of the changes in instantaneous energy of each segment were summed. By doing this, the positive and negative work values did not cancel each other out, however, the work was overestimated for some types of movements because the equation did not allow for energy transfers within or between segments.

Winter (1978) extended the pseudo-work equation so that the work was calculated for the total body, not just the segments, and also expanded the equation to include energy transfer within and between segments. This was termed the internal work equation (denoted W_{wb}). Unfortunately, the mathematical validity and reliability of this equation was never proven. Nevertheless this approach has been applied in a number of studies examining a wide range of activities. For example it was used to calculate the work involved in walking (Winter, 1978), in load carriage (Pierrynowski, 1981), in cross-country skiing (Norman et al., 1985), in rowing (Martindale and Robertson, 1984) and in running (Williams and Cavanagh, 1983). For comparison purposes we therefore used a modified version of the W_{wb} model in this study, which we termed "absolute work".

A number of researchers have proposed many variations of the W_{wb} model with differing limitations on between segment energy transfers and/or computational adjustments for biological factors that influence internal work (i.e., Pierrynowski et al., 1980; Williams and Cavanagh, 1983). In this study we allowed unlimited between segment energy transfer as any limitation to this is arbitrary. Although there are many biological factors that influence internal work (for example: metabolic cost is reduced by elastic storage of energy), we are not able to directly measure their effect which makes their quantification rather arbitrary. We did not include any of these factors in our study because of our inability to measure them accurately.

Although an improvement on what came before, the internal work equations are still limited in their applicability. There are two main points on which they falter: between segment transfer is always assumed to have occurred; conservative movements are not recognized and are therefore overestimated. The following examples should help clarify these points (cf., Wells 1988). Negative work is performed when a person lowers an arm from a raised position. Positive work is performed when a person raises a leg from a lowered position. When these movements are performed asynchronously the internal work equations compute the work involved correctly. When these movements are performed simultaneously, however, the assumption inherent in the calculations is that the decrease in energy of the lowering limb is transferred (causes) the increase in energy of the raising limb. In this case between segment energy transfer is assumed to have occurred when, in fact, it didn't, and the total body work is therefore underestimated. As well, for conservative movements (i.e., an ideal pendulum) the energy approach shows that work was done when in fact no internal or external work was necessary. This may not be a significant problem, however, because few human movements are fully conservative.

A method of calculating work that eliminates these problems is joint power analysis. This method computes the powers produced by the moments of force at the joints then integrates with respect to time to get work values. Winter (1987) outlined the principles underlying this method. Although the basic equations have been around for a long time (first described by Elftman, 1939), this method of determining work has not been used often. This is likely because a reliable device for measuring ground reaction forces is needed and the calculations are much more complex than those involved in Winter's internal work. The problem with Elftman's equations was that the positive and negative power values cancelled each other before they were integrated to find work, thereby underestimating the internal mechanical work done.

Aleshinsky (1986) eliminated this problem by modifying the power equations so the **absolute** power values were summed. He also mathematically established the validity of this method and the invalidity of the energy approach. A slightly modified version of Aleshinsky's equation was used in this study and was termed the "absolute power" method. Chapman (1987) used this approach in a study that compared normal running (efficient) with modified running styles (inefficient), to see if differences could be distinguished. Unfortunately, Chapman's study had only one subject and compared total work values without accounting for the external work done.

Purpose

In this study a protocol similar to Chapman's was used to determine if the absolute power approach was sensitive enough to detect inefficient movement patterns. Internal work, calculated using the absolute power approach, was divided by the running velocity and body mass to obtain what is termed the "internal biomechanical cost" (denoted IBC). The IBC for the mean normal run (presumably efficient) was compared to IBC values of each of the modified runs (presumably inefficient) for four male and four female elite level runners. These IBC values were also contrasted to the internal biomechanical cost computed using the absolute work approach as the measure of internal work, to determine which method was better able to detect the inefficiencies of the modified runs.

METHODOLOGY

The subjects used were middle distance or cross-country runners, with a minimum of two years of training and competition. There were four females and four males, all above 18 years of age. A sample of the consent form given to each subject is in Appendix B. Age, gender, height, weight and various segment lengths of each subject were recorded. Markers were placed at the joint centres of each segment. To reduce the risk of injury subjects did a warm-up, including several practice runs. This allowed them to find a comfortable running pace and become accustomed to the running surface and laboratory set-up. They were then filmed at 100 frames per second (Locam camera) running across a force platform (Kistler) which measured the ground reaction forces at a 200 Hz sampling rate. Each subject did five trials of normal runs followed by one trial each of four modified runs. The modified runs were: exaggerated knee flexion (EKF), overstriding (OS), stiff knees (SK), and exaggerated arm swing (EAS), (cf. Chapman et al., 1987). Practice of the each of the modified runs occurred after a verbal description and physical demonstration, with the goal being a run that was as exagerrated as possible while still maintaining accuracy in hitting the force plate. The film data were synchronized with the force plate data using custom software.

Link segment models combined with inverse dynamics were used to calculate the joint moments and forces. From this internal and external work were calculated using two different techniques. One technique used the changes in segmental energy to calculate internal and external work (Winter, 1990). The other technique used the integration of joint powers to calculate internal and external work (Aleshinsky, 1986).

External Work

When calculating external work the energy approach sums the segmental energy changes during the movement; which is equal to subtracting the initial total body energy from the final total body energy.

$$W_{ext} = \sum_{n=1}^{N} \sum_{s=1}^{S} \Delta E_{s_n} = E_{T_N} - E_{T_i}$$

W_{ext}	external work as calculated by the energy approach
N	the number of frames in the cycle of motion
S	the number of body segments
ΔE_S	change in segmental energy
E_{T_N}	final total body energy
E_{T_I}	initial total body energy

The power approach sums the changes in joint powers over time, where joint power is the product of the joint moment and the angular velocity.

$$W'_{ext} = \sum_{n=1}^{N} \sum_{j=1}^{J} P_{jn} \Delta t = \sum_{n=1}^{N} \sum_{j=1}^{J} M_{jn} \omega_{jn} \Delta t$$

W'_{ext}	external work as calculated by the power approach
P_j	the joint power
M_j	the joint moment
ω_j	the joint angular velocity
Δt	sampling time = 1/100 s
J	the number of joints

Internal Work

The methods for calculating internal mechanical work (W_{wb} (Winter, 1990) and absolute power (Aleshinsky 1986)) actually calculate a total work value. To find the internal work value, the external work must be subtracted from the equation (cf., Pierrynowski et al., 1980). For the W_{wb} method the energy-based external work was subtracted and this corrected equation was called absolute work. For the absolute power approach the power-based external work was subtracted. It was hoped that by doing this the modeling errors would be minimized (Robertson and Winter, 1980).

The corrected internal work equations are as follows:

$$\text{Absolute work} = \sum_{n=1}^{N} \left| \sum_{s=1}^{S} \Delta E_{sn} \right| - W_{ext}$$

Absolute work   Winter's internal work equation (W_{wb}) corrected for external work (energy approach)

$$\text{Absolute power} = \sum_{n=1}^{N} \sum_{j=1}^{J} \left| P_{jn} \right| \Delta t - W'_{ext}$$

Trapezoidal integration was used to compute the time integrals.

Internal Biomechanical Cost and Statistics

To reduce the risk of injury as the subjects performed the modified runs velocity was not controlled. For an accurate comparison of the normal and modified runs to take place the velocity then had to be normalized. To do this the internal work was divided by the running velocity. In order that comparisons between subjects could be made internal work was also divided by body mass. The resulting value was termed the internal biomechanical cost (IBC).

IBC = internal work/(running velocity*body mass)

The averaged IBC values, calculated using the absolute power method, for the normal runs were compared to the IBC values for each of the modified runs using a planned comparison with a Bonferroni corrected alpha level. This method had greater flexibility than an ANOVA followed by a Dunnett post-hoc test would have (Darlington, 1990). Since it has already been proven that the energy approach is inaccurate (Aleshinsky, 1986) it was pointless to do a similar statistical comparison (normal vs.

modified) for the energy approach. A comparison was done graphically, however, between the averaged IBC values for the normal and modified runs from the absolute work equation and the averaged IBC values for the normal and modified runs from the absolute power equation. This gave an indication of how closely the equations corresponded and was an interesting comparison to Chapman's results. Since external work values from the two methods are theoretically equal these results were also graphically compared.

RESULTS AND DISCUSSION

Eight subjects performed five normal runs and four modified runs each. For three of the subjects one normal run contained invalid data (i.e., the subject's foot was off the edge of the force platform) and was discarded. The internal biomechanical costs of the normal runs for each subject were averaged together to produce a "mean normal run" value for that subject. This was done for both the absolute work and absolute power methods. For the absolute power method the mean normal run of each subject was statistically compared to their modified runs. Since four t-tests were being performed, a Bonferroni corrected alpha level of 0.0125 was used (p values in Appendix C). As can be seen in the IBC graphs on the following three pages (Figures 1-8) all but two of the thirty-two modified runs (8 subjects*4 runs) were significantly different than the mean normal runs. The open squares represent that subject's mean normal run value, and the black triangles represent the statistical cutoff of 98.75%. Since the inefficient modified runs (black squares) were statistically different than the mean normal run in 94% of the cases we can conclude that the absolute power approach is sensitive enough to detect inefficiencies.

The two modified runs that were not significantly different than the mean normal runs were both exaggerated arm swing (EAS) for subjects VW and HO. As can be seen in the IBC graphs (Figures 1-8) the lowest cost of modified running is often that of EAS, even though all subjects performed extremely exaggerated swings. The implication of this result is that during normal distance running an arm swing that is only slightly exaggerated will have very little affect on the total amount of work done. The implication for coaches is that errors in arm action are relatively less important than other aspects of the person's run.

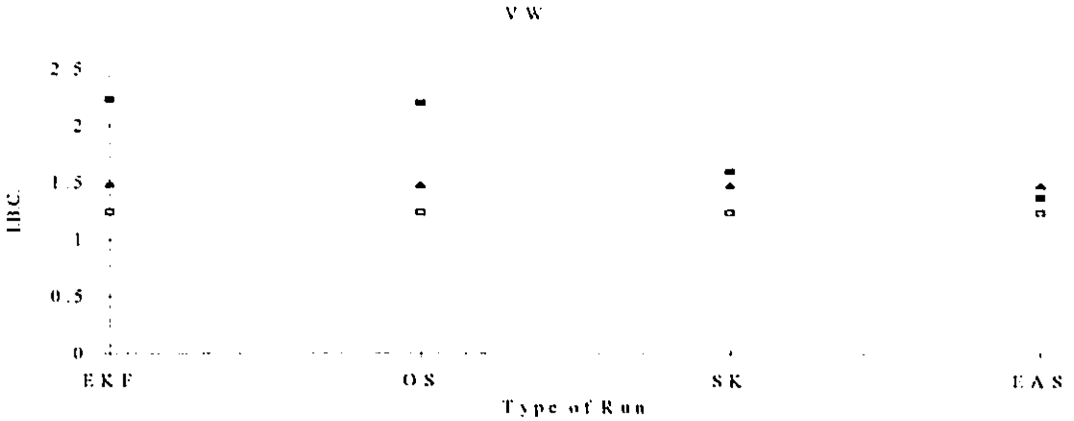


Figure 1: Internal Biomechanical Cost of Modified Runs for subject VW (female)

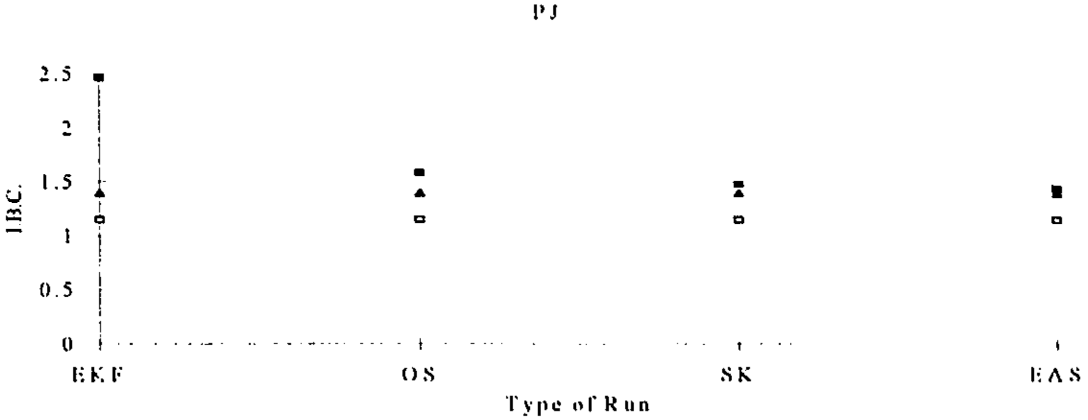


Figure 2: Internal Biomechanical Cost of Modified Runs for subject PJ (male)

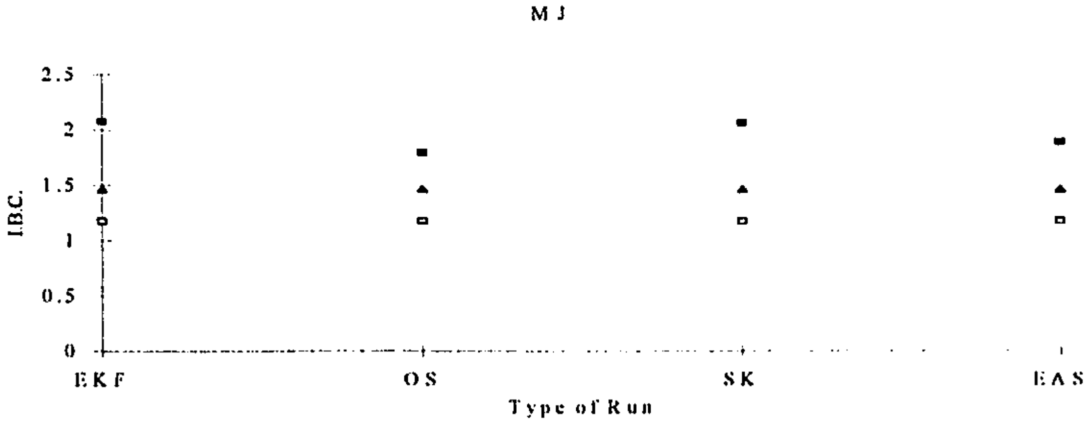


Figure 3: Internal Biomechanical Cost of Modified Runs for subject MJ (male)

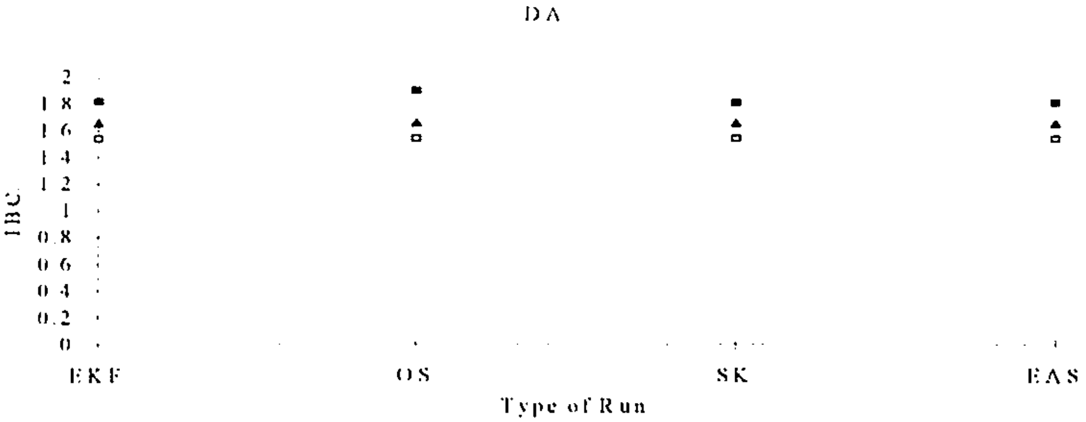


Figure 4: Internal Biomechanical Cost of Modified Runs for subject DA (male)

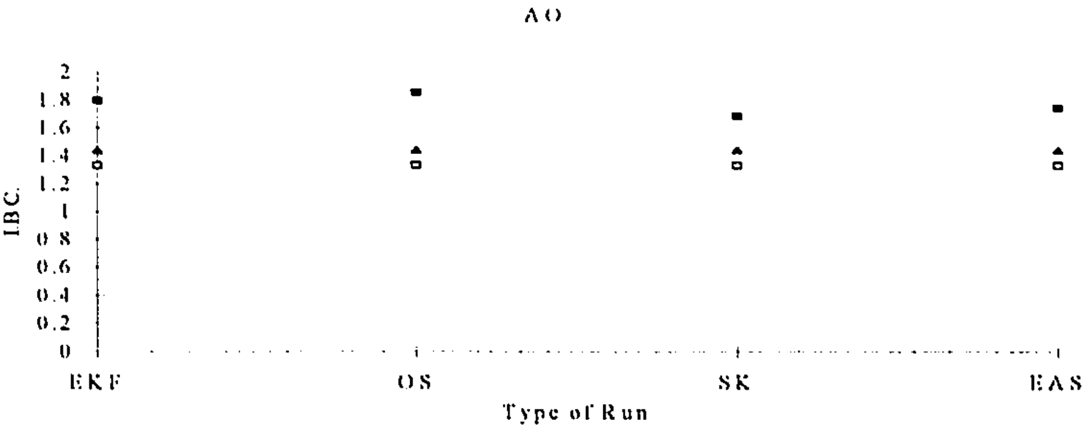


Figure 5: Internal Biomechanical Cost of Modified Runs for subject AO (female)

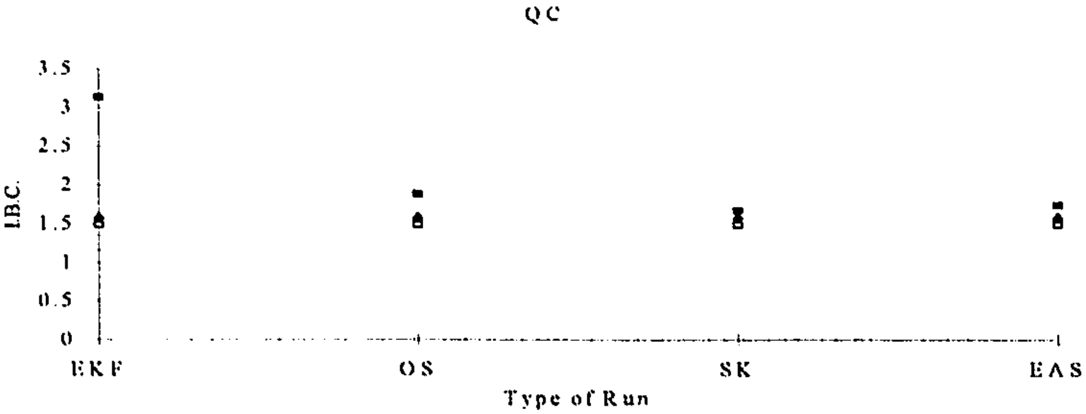


Figure 6: Internal Biomechanical Cost of Modified Runs for subject QC (male)

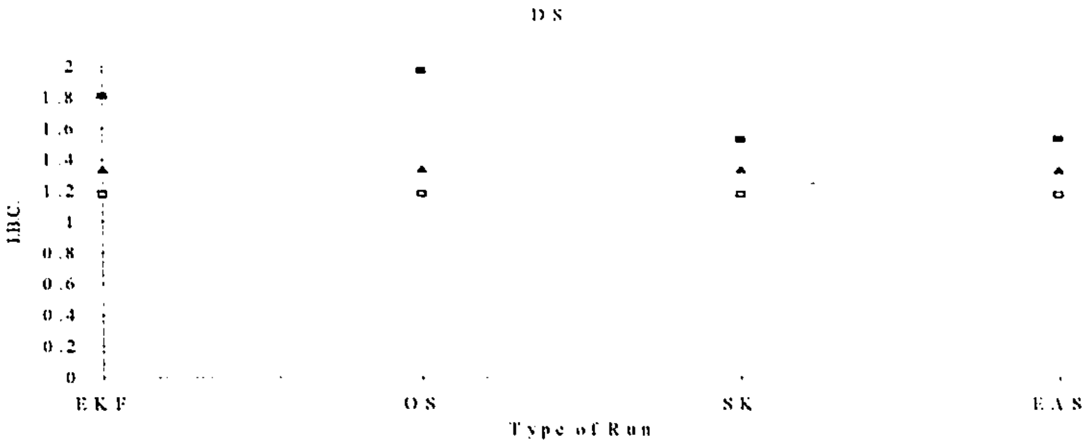


Figure 7: Internal Biomechanical Cost of Modified Runs for subject DS (female)

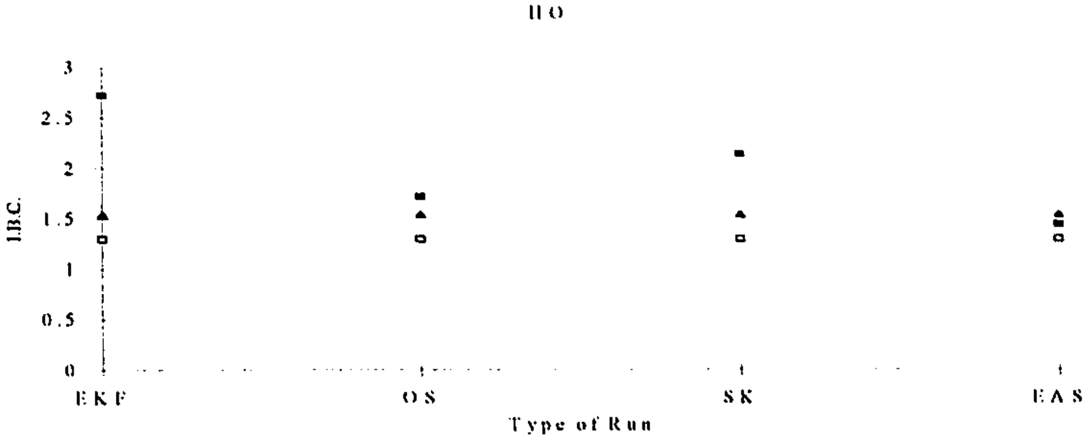


Figure 8: Internal Biomechanical Cost of Modified Runs for subject HO (female)

Since Aleshinsky (1986) has shown that the absolute work method is not mathematically valid, formal statistical analysis was not performed. To illustrate that the absolute work method was less able to detect inefficient running a truth table was constructed. For this table a modified run that was more than two standard deviations away from the mean normal run was called "True". A modified run that was less than two standard deviations away from the mean normal run was called "False".

Table 1: The Ability of Absolute Work to Detect Inefficiencies

SUBJECT	EKF	OS	SK	EAS
VW (female)	**False**	True	**False**	True
AO (female)	True	True	True	True
DS (female)	True	True	**False**	**False**
HO (female)	True	True	True	**False**
MJ (male)	True	True	**False**	**False**
PJ (male)	**False**	**False**	**False**	**False**
DA (male)	**False**	**False**	**False**	**False**
QC (male)	True	True	**False**	**False**

Even with a much more lenient cutoff, 95% rather than 98.75%, the absolute work method only detected the inefficiencies of the modified runs in 15 of the 32 cases (46%) compared to 30 of 32 detected by the absolute power method. Absolute work was not consistent in the type of modified runs that it could detect, although it generally performed better with exaggerated knee flexion (EKF) and overstriding (OS) than it did with stiff knees (SK) and exaggerated arm swing (EAS). It was able to detect the differences in all four modified runs for only one subject. The relative inability of absolute work to detect the inefficient modified runs experimentally confirms the mathematical invalidity of this model.

To compare the internal biomechanical cost values of the absolute work method with those found using the absolute power method a grand average across all subjects was performed. Figure 9 shows these results.

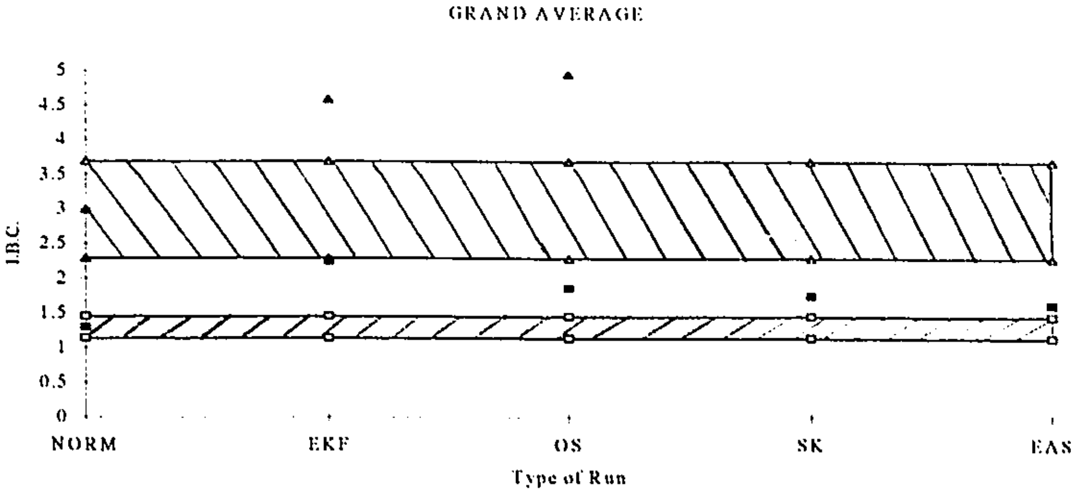


Figure 9: Comparison of the Averaged IBC Values for the Absolute Work and Absolute Power Methods

The mean normal run is the value labeled "NORM" on the abscissa. The lower NORM value represents absolute power (black square) and the upper represents absolute work (black triangle). The lower shaded area (between the open squares) is the average internal biomechanical cost (IBC) of the normal runs plus or minus one standard deviation calculated using the absolute power approach. The upper shaded area (between the open triangles) is average IBC of the normal runs plus or minus one standard deviation calculated using the absolute work approach. Only two of the modified runs, exaggerated knee flexion (EKF) and overstriding (OS) were more than one standard deviation away from the mean normal run for the absolute work method (black triangles). On the other hand all four of the modified runs were more than one standard deviation away from the mean normal run for the absolute power method (black squares). This once again confirms that the absolute power method was better able to detect mechanical inefficiency. Also of note in this graph are the magnitudes of the standard deviations. The standard deviation for the absolute work method was approximately 4.4 times larger than that of the absolute power method. Since standard deviation is a measure of variability, these results show that the absolute work method was more variable and less reliable than the absolute power method.

Figures 10 and 11 show the external work for normal and modified running respectively. As mentioned previously the external work values for absolute power are theoretically equal to the external work values of absolute work. It is obvious from these results that this is not the case. During normal running, using the absolute power method (dark squares), five of the eight subjects were speeding up as they crossed the force plate (speeding up = positive external work; slowing down = negative external work). Since the force platform was only 8 meters from their starting position (a limitation of our laboratory configuration) this is not surprising. The other three subjects showed varying values, sometimes speeding up sometimes slowing down, but all close to zero. None of the external work values for the absolute power method exceeded 100 J during normal running. During normal running using the absolute work method (empty squares), only three of the subjects were speeding up and the rest of the subjects had values that varied extensively in what appears to be a random pattern. The values for absolute work were on average 2-3 times greater than the absolute power values. All values were more variable during modified running but the same major differences between the methods, greater variability and larger values for absolute work, held true. From these results we can conclude that the absolute power method is better for determining external work as well as internal work.

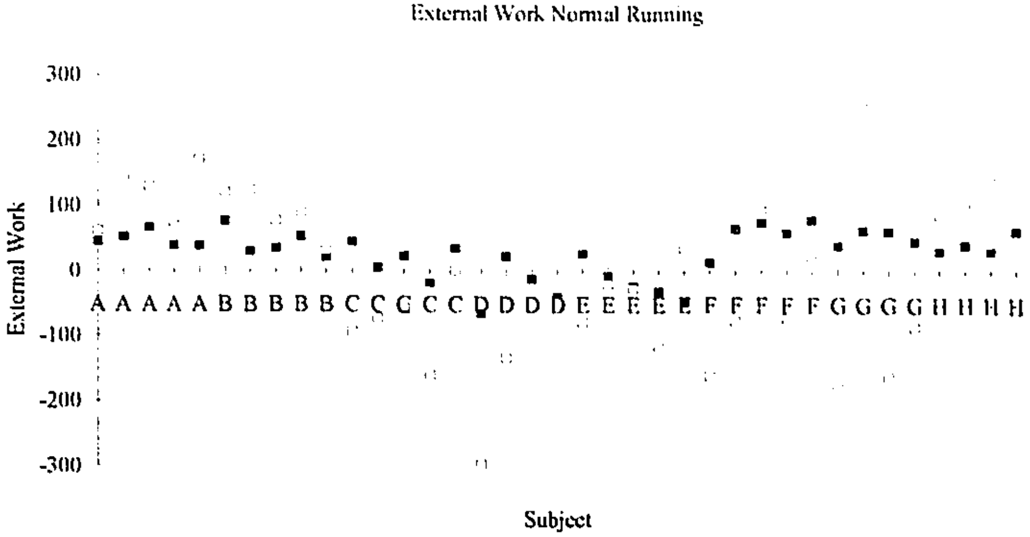
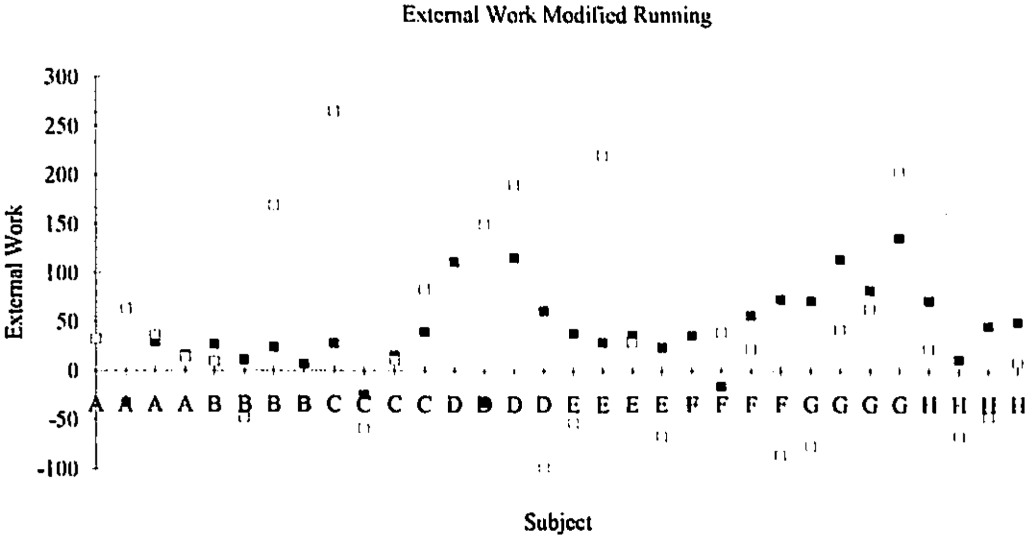


Figure 10: Comparison of External Work Values for Normal Running

Figure 11: Comparison of External Work Values for Modified Running



The supposition behind the absolute power method is that negative work contributes significantly to the total work done and must therefore be included in the calculation of this value. Table 2 describes the percentage contributions of positive and negative work to the total work done as both overall values and at each joint. As mentioned in the Methodology section, external work is embedded in the total work. The positive and negative work percentages therefore add up to 100%, and external work is a portion of this. These values were found by randomly sampling one normal running trial from each subject and then averaging across the eight subjects.

Table 2: Positive and Negative Work as a Percentage of Total Work

Grand Average	% POSITIVE	% NEGATIVE
RT. ANKLE	14.5	4.9
RT. KNEE	6.5	14.3
RT. HIP	14.3	10.2
LT. ANKLE	0.4	0.1
LT. KNEE	0.2	9.6
LT. HIP	12.9	3.2
RT. ELBOW	0.4	0.2
RT. SHOULDER	2.1	1.5
LT. ELBOW	0.7	0.7
LT. SHOULDER	1.6	1.0
RT. LEG TOTAL	35.2	29.4
LT. LEG TOTAL	13.5	12.9
RT. ARM TOTAL	2.5	1.7
LT. ARM TOTAL	2.3	1.7
TOTAL	**53.9**	**46.1**

It was the right foot that contacted the force platform during the trials. Since our laboratory configuration prevented the use of two force platforms only one step (left foot toe-off to right foot toe-off) was analyzed, not a full stride. The values for the right leg encompass the last part of swing phase and all of stance phase and the values for the left leg encompass the first part of swing phase. It is evident from Table 2 that negative work contributed a great deal (46%) thereby confirming the original supposition. The joint-by-joint breakdown shows which joints contributed the most work during the activity. For the stance leg (right leg) positive work was done mostly at the ankle and hip, with negative work done mostly at the knee and hip. For the swing leg (left leg) positive work was done almost exclusively at the hip and negative work was done primarily at the knee with a small amount done at the hip. Very little work was done by either arm with the greatest amount (2.5%) done by the right arm. With such a small contribution to the total work it was impossible for this limb to have been a large source of inefficiency. This reinforces our previous conclusion that arm swing is a relatively unimportant aspect of running style for distance running.

Coaches and therapists can use this movement analysis to effectively direct training and rehabilitation efforts. For example the large percentages of positive work done at the hip and ankle indicate that these were the prime movers. Since it was positive work concentric training of the muscles involved would be the most effective. A large percentage of negative work was done at the knee indicating that the muscles at this joint were working as stabilizers and shock absorbers. Eccentric training would be the most effective for these muscles. Two other results were of note. External work was only 9% of the total and the upper body contributed only minimally.

CONCLUSION

The absolute power method was sensitive enough to detect the inefficient modified runs. In addition to detecting mechanical inefficiency more frequently than the absolute work method did, the absolute power method was demonstrably more reliable in two other ways: the standard deviation was at least three times less than the standard deviation of the absolute work method (based on a subject-by-subject analysis) and the external work was much less variable and much closer to zero than the external work found using the absolute work method. It is therefore strongly recommended that the absolute power method be used whenever feasible. The absolute power approach is also a valuable tool for determining which joints contribute the most work to the movement and where inefficiencies are likely to occur.

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APPENDIX A - REVIEW OF LITERATURE

REVIEW OF LITERATURE

The greatest problem encountered when attempting to describe the efficiency of a movement is our inability to quantify the complexity of the human system. The models we use are gross oversimplifications of reality. This is largely because we are unable to measure with accuracy many of the factors that complicate movement. For example, the extent that metabolic cost of positive work is greater than the cost of negative work, the degree that passive structures and the stretch reflex contribute to reducing the metabolic cost of a movement, and the effect of elastic storage of energy, to name just a few. There is also difficulty in determining the cost involved in moving body segments through a cyclic motion. This cost is termed internal work.

External work calculations do not take into account the cost involved in moving the body segments. If the movement being performed is cyclic the external work calculations will severely underestimate the metabolic cost of the movement (i.e., the zero work paradox mentioned previously). Realizing this, researchers have focused on developing calculations that would calculate the internal work (the metabolic cost of limb movement).

Two basic models have been developed to estimate values for internal work. One is based on the summation of energy changes. The other is based on the integration and summation of joint powers. Attempts have been made to include some of the complicating factors in the basic models, but because we can't measure these factors directly the modifications have been primarily educated guesses. There is no consensus on what is the most accurate method of calculating mechanical energy, although we hope with this research to show that the method we are advocating, a modified power approach (referred to as the absolute power approach), is more accurate than standard measures, even if it is far from ideal.

The Energy-Based Models

The energy-based model has been much more widely used than the joint power based model. This is probably because it is easier to calculate and there is no need for instrumentation to measure ground reaction forces. The idea of using potential and kinetic energy changes to describe human work was first detailed by Fenn (1929). He described mechanical work as the sum of the energy increases (potential, kinetic translational and rotational) for each segment of the body. Although a vital first step, this method had three major flaws. The first was that it did not allow for conservation of energy within a segment, also called within segment transfer (Winter, 1978). Energy conservation (within segment transfer) is the change of energy from one form to another form (i.e., from potential to kinetic) and does not require work to be performed. Fenn's method would therefore overestimate work in this instance. The second flaw in this method was that it did not allow for energy transfer between segments. Between segment transfer is the exchange of energy across segments, in which energy leaves one segment and enters one or more other segments. No work is done by the segment that increases in energy. For example, when raising on tiptoes, work is done at the ankle and energy is transferred between segments, so the rest of the body increases in potential energy without doing work. Not taking between segment energy transfers into account would also result in an overestimation of work. The third flaw is referred to as the zero work paradox (Aleshinsky, 1986): positive and negative work values cancel each other out when summed. This leads to an underestimation of the work done, and in situations when the positive and negative work values are equal (i.e., cyclic movements), an erroneous zero amount of work done.

Norman, Sharratt, Pezzack and Noble (1976) modified Fenn's approach, and summed the **absolute values** of the energy changes in each segment. This method, termed "pseudo-work", eliminated the zero work paradox (all values being summed were now positive, so didn't cancel). They used a twelve segment model, applied to three subjects running at 50, 66 and 100% of MVO_2 on a treadmill. An important conclusion of this study was the validation of link segment models as a more accurate representation of reality than point-mass systems (where work is calculated from the movement of the body's centre of gravity). Although this study was a major stepping stone in the refinement of work calculations, it still led to overestimation of the work because it did not allow for energy exchanges within and between segments.

Winter (1978) addressed these problems by presenting equations with which energy transfer within and between segments could be calculated, known as "internal work" calculations, denoted W_{wb}. The emphasis of this research was on the energy equations, and how the interpretation of them leads to a description of the energy flow (generation, absorption and transfer) through an entire system, an improvement on the segmental approach of pseudo-work. The article also briefly describes the calculations for determining the work done at the joints by muscles (joint power analysis) and how the results could add to the researcher's ability to describe the movement. Work was found by determining the energy flow within and between segments with respect to time. Winter also critiqued the literature up to that point: he examined the errors involved in attempting to calculate work by measuring the movement of the centre of gravity ("point-mass" approach), the importance of including between segment energy transfer in work calculations and the ambiguities in the literature regarding the calculation of efficiency of movement. He also tried to bring cohesion to the research community by presenting a set of definitions for commonly used terms, many of which are still used today. The application of energy analysis to training was discussed for running and jumping, and future research goals were outlined.

With a basic model now established, the next goal was to more fully describe the energy flow through and within the segments, and to attempt to account for some of the biological factors that affect the energy required for the movement. A large number of studies were published around this time, each with variations on the limitations to energy flow and taking into account various biological factors. An example of this type of experiment is the study by Pierrynowski, Winter and Norman (1980). They investigated the extent of energy conservation during walking by partitioning the segmental energy into muscular activity and passive exchanges. They found that about two thirds of segmental energy changes for six male university students walking on a flat treadmill could be attributed to passive (conservative) energy exchanges within or between segments. They therefore concluded that normal walking was a highly conservative event. This study also examined the mechanical efficiency of the movement. Knowing that eccentric contractions (negative work) have a lower metabolic cost than concentric contractions (positive work), these researchers varied the positive and negative work efficiency values and found that this resulted in widely varying total efficiency values. When negative work was assumed to be three times more efficient than positive work (130% efficiency to 43.3% efficiency), the overall efficiency of the movement was found to be 65%. Unfortunately, the differential cost of positive versus negative work was not directly measurable and any changes to work efficiency values were therefore only educated guesses.

The description of energy flow was the focus of many studies. Although researchers agree that energy transfers between segments occur, whether these transfers should be limited (i.e., to adjacent segments) has been a matter of much debate. Representative of this was the study by Williams and Cavanagh (1983) who used 31 well trained distance runners and three-dimensional cine data for the segmental energy analysis. These researchers varied the assumptions made regarding the extent of energy transfer between segments, the differential metabolic cost of positive and negative work, the amount of passive work and the extent of elastic energy storage. They pointed out how a model with unlimited between segment energy transfers will fail in certain situations. As a result of this they decided that between segment energy transfers should be limited to adjacent segments only. Included in their calculations was a fractional value for negative work (reflecting its lower metabolic cost); in addition, a value for elastic energy storage was subtracted from the basic equations. They found that varying these values led to huge differences in the resultant mechanical power. Even when limited to "reasonable upper and lower bounds" there was a 270% difference in power values. The importance of this study was that it correctly emphasized that the there was no single model that was accurate. Furthermore, since it is not possible to directly measure the biological factors included in this study (i.e., elastic energy storage, differential metabolic cost of positive and negative work), any numerical value included in the equations was merely an educated guess. As explained by these researchers, unlimited between segment energy transfer was not always valid. A model that limits between segment transfer will also fail in certain situations, making any limitation to energy transfer arbitrary.

The widely varying results in the above study illustrate the questions faced by researchers in this field: why do different studies purporting to measure the same thing produce wildly different values? What is the "best" model? What factors should be included in the model and what values should they have? These questions were examined in a symposium paper by Williams in 1985. He pointed out that although many studies have widely varying results this is largely due to differing "guesstimate" values for: energy requirements of concentric and eccentric contractions, between segment energy transfer, elastic storage of energy and limitations to the joint range of motion. These factors are known to affect the energy requirements of movement but it is beyond current capabilities to measure their influence. As a result, researchers used their own "best guess" values when including these factors in their equations, and ended up with different results than other studies that purported to measure the same things. Williams concluded that it is currently impossible to clearly define the "best" method of calculating work.

The Joint Power Models

In search of a more accurate model, attention has turned to joint power analysis. Although this method has been around for quite some time, it is only recently that its full value has been recognized. This slow coming of age is probably because more equipment is involved (an accurate force platform is needed to measure ground reaction forces) and the level of complexity of the equations is greater than for the energy method. This method was first described by Elftman in two research papers published in 1939. The first (1939a) described the application of inverse dynamics to determine the forces and moments present during movement. The second (1939b) described the role of muscles in locomotion. Using D'Alembert's principle, he detailed how the forces and torques for the whole leg could be determined (one segment at a time) from knowing the ground reaction force for a given instant in time. It is the integration of these instantaneous values that give us joint power analysis. He combined these results with the energy method to describe the flow of energy through the body. In the second article, Elftman used this knowledge of energy flow to describe the multiple roles muscles play in locomotion. He concluded that muscles "exert torques which cooperate with the other forces present in determining the movements of the body and regulate energy exchange, by transmitting, absorbing, releasing and dissipating energy". He also explained how the transmission of energy through a muscle required no work. In addition, he described the necessity of energy dissipation as a function of musculature. The role of muscles in locomotion was examined using models containing only single joint muscles, or only tri-articular muscles. The results were used to illustrate the characteristics and benefits of the body's actual one and two joint musculature. Joint power analysis in other studies was initially used in a similar manner to Elftman's studies, as an addition to the energy method to more fully describe the movement or as a comparative work value.

One example of how joint power methods were used to better the understanding of what was involved in a movement was the 1976 study by Cappozzo, Figura, Marchetti and Pedotti. In their study they used a combination of the energy and joint power methods as a way of describing the interplay of various forces and how this affected walking. Five subjects were filmed walking across a Kistler force platform at their natural speed. EMGs were collected for thirteen muscles on each subject. An eight segment rigid body model was used in the calculations. This study examined the roles of muscular, gravitational and inertial forces in relation to the kinematics, dynamics and energy levels of the movement. The result was a model of how the interplay between muscular and external forces affected movement and how they were reflected in the energy patterns. From this came a detailed description of gait patterns and the mechanisms involved in displacement of the body. The model used in this study failed during heel-strike, but was reliable during the rest of the movement. They concluded that this interplay of forces could be used to efficiently study other movements, such as pathological gait. But the anterior-posterior rotations of the pelvis and HAT were neglected in this study and this model may therefore be too restrictive to be used in the study of other movements. Although these rotations are not large in normal walking they may be an integral part of some pathological gaits.

Winter and Robertson (1978) compared the results of the energy and joint power calculations in their examination of the energy and torque patterns of walking. The walking gaits of two subjects walking at three speeds (fast, medium and slow) were filmed and force plate data were collected. A three segment model of the leg was used in the calculations. This model was different than the norm because the sum of the moments was taken about the knee joint not the centre of gravity of the shank. As the authors point out, this enabled them to partition the knee moments into three components: muscular, gravitational, and the moment due to the linear acceleration of the knee joint. They found that the interaction of these three forces caused shank rotation. By using the absolute angular velocity when calculating muscle power these researchers were able to define when the muscle was being used to transfer energy, in addition to the already known functions of generating and absorbing energy. By combining the energy flow analysis and the joint power analysis, a model of the leg was developed which detailed the patterns of energy generation, absorption and transfer through the joints during six stages of gait. This model, which synthesized the important information of the two calculation methods, had a large impact on the way movement analysis was subsequently performed.

Robertson and Winter (1980) had a twofold reason for using both energy and joint power calculations: to more fully explain the changes in mechanical energy of the segments; and to compare the results of the two types of analysis. Two male subjects were filmed as they walked across a force platform at four different speeds. The results of the two calculation methods were compared in an effort to validate the results of joint power analysis. In theory, the rates of change of mechanical energy for the segments should be equal to the total powers acting on the segments. They found a close correspondence between the results for everything except the ankle powers during weight-acceptance and push-off. This validated the use of joint power analysis and also supported the assumption that the joints could be accurately modeled as ideal hinges. Through examination of the results of the two sets of calculations, the conclusion was reached that joint energy transfers were as important as energy generation and absorption in explaining segmental energy changes. This meant that a significant amount of energy change in a segment may not be the direct result of energy generation or absorption in that segment, but may be energy that has been transferred into or out of that segment through the joints or the musculature.

Through the use of these models, the researchers were able to state when musculature was generating or absorbing energy. It was not possible, however, to state precisely which muscles were being activated and to what extent - all the models represented the musculature as SEMs (single equivalent muscle). Connecting the models more closely to anatomy, Wells and Evans (1987) examined the mechanical energy savings presented by two-joint muscles. Five females were tested under two isometric conditions. In the first condition, forty-nine combinations of hip and knee joint moments were produced, and EMG readings were taken from eight muscles. In the second, the subjects generated directional forces, and EMGs were recorded for ten muscles. In a third experiment, two subjects walked at three speeds (slow, natural and fast) across a force platform while being filmed. EMG readings were taken from six muscles. The EMG readings from all three experiments were fed into a decision algorithm which partitioned the muscle moments between one- and two-joint muscles. Predicted two-joint muscle activity agreed well with measured EMG, but the activity level of one-joint musculature was underestimated. From the results of this study it was concluded that there is an internal strategy in which the more efficient two-joint muscles are preferentially recruited, given appropriate circumstances. The authors also concluded that the underestimation of the activity level of single joint muscles was likely the result of antagonistic and stabilizing functions which weren't included in the model.

The previous study formed the basis for another study by Wells (1988) that assessed the role of two-joint muscles and segmental energy transfer and the implications this has for energy savings. He used both modified joint power equations and modified energy equations to estimate the energy savings resulting from the use of one- and two-joint musculature (rather than only one-joint muscles). Data were collected on three male subjects walking at three different velocities (slow, normal and fast), and on one male performing a maximal vertical jump. Both cine and force platform data were collected. A decision algorithm, similar to the one used in the previous study, was used to select an appropriate activation pattern for two scenarios: activation of only single joint muscles and activation of both one- and two-joint muscles. For the walking trials activation of two-joint muscles resulted in a reduction of the work done, especially at the knee joint. The estimated average saving of 11.6% supports the theory, but quantitative values could not be accurately determined because muscle forces were only predicted, not measured.

Jumping showed much smaller energy savings, present only in the countermovement. The authors speculated that this was the result of the extensors being active at all of the joints, and two-joint muscles being used primarily as energy transfer agents. Although this research provides valuable insights into muscle activation and energy savings, we are still far from the point where this information could be assimilated into the current work models.

It has only been fairly recently that joint power analysis has been used on its own to model movements. The concepts involved in the power approach were detailed in a review article by Winter (1987). Performance of a movement was explained in terms of the combined efficiency of the metabolic and neural control systems. The joint power equations were explained in terms how they represented energy flow (generation, absorption, and transfer) through a system of segments. The wealth of information that can be derived from the joint power calculations was illustrated through an analysis of running. The limitations of the biomechanical model were pointed out and the author concluded with a brief look at possible future directions, including making the model closer to anatomy (i.e., being able to describe the role of separate muscles). The problem encountered with this method was similar to that earlier encountered with the energy method: the positive and negative power values cancel each other before they are integrated to find the work value. This leads to an underestimation of the work value.

Aleshinsky (1986) overcame this by modifying the power equations. Power was calculated directly from the integration of the product of the moments and angular velocities. The **absolute value** of the powers were then integrated to find the work. In his five part article Aleshinsky detailed the development of the joint power equations for one link and multi-link models, and critiqued the energy based approach. In Part I, the author discussed the problems with the external work approach and with the energy equations. He then detailed the analysis of a one-link system in terms of joint power analysis. In Part II, this analysis was expanded to a multi-link model, and the failure of the "external"/"internal" work approach was explained. Part III was the mathematical description of how mechanical energy expenditure (MEE) could be reduced, for a one-link system, through energy transformations between: rotational and translational fractions of the kinetic energy (also called F-sources compensation); and potential and kinetic energy (*mg*-source compensation). Part IV was a critique of the calculations that have been used for finding energy transfers within and/or between segments. He concluded that W_{wb} (Winter's name for within and between segment energy transfers), could be used as the lowest limit of mechanical energy expenditure but that it only is equal to the MEE when all the joint powers have the same signs or when the powers of all M-sources but one are equal to zero (no external energy sources). The author concluded that calculations for within segment transfer (W_w) and for no transfer (Wn) were not realistic representations of the movement and could not lead to correct results. Part V described mechanical energy expenditure (MEE) reduction for a multi-link segment. It was concluded that MEE reduction was a result of energy transformations within links (as discussed in Part III) and/or energy transfers between links. These articles mathematically illustrate the faults and limitations of the energy based models. The conclusion reached was that joint power analysis provides the best mathematical representation of physical reality.

Chapman et al. (1987) also recognized the problem inherent in Elftman's joint power approach. They illustrated it by pointing out that it is possible to have two joints with power values of opposite signs and equal magnitudes. There would be a metabolic cost to each set of muscles, but the powers would cancel out before being integrated. The authors suggested "integrating the absolute value of each muscle moment power separately"; the same procedure that was mathematically validated by Aleshinsky. Chapman used the term "Total Body Work (TBW)" to describe this method. "Absolute power" will be the term used to describe a modified version of this equation in the current study. In Chapman's study, one male subject was filmed running across a force platform using five different running styles (one preferred, four modified). The same stride length and frequency was used for all runs. Work was calculated using W_n, W_w, W_{wb}, and TBW. Total body impulse (TBI) was calculated by "taking the time integral of the absolute value of joint moments individually, and summing across joints". This value will increase when the muscles are in isometric tension, which doesn't show up in TBW. Although the normal run was assumed to be the most efficient, running with stiff-knees had lower work values for all the calculation methods. For W_{wb} three of the four modified runs had work values lower than the normal run. TBI showed the lowest value for the normal run. W_{wb} and TBW had similar values for the normal run, but very different values for the modified runs. The authors took this as an indication of the underestimation of work for W_{wb} resulting from positive and negative values canceling each other out. They concluded that TBW was logically a better estimate of the cost to the musculature than estimates based on changes in energy. Unfortunately, only one subject was used in this study, the results were partially ambiguous and total work values were compared, not internal work values. It was not necessary to compare TBW to W_n and W_w because, as Aleshinsky has mathematically proven, these are not valid models.

Summary

The energy approach has produced many different models, most differences being the result of varying values given to biological factors. As illustrated in this review, most of the biological factors that affect energy costs cannot be measured accurately, and therefore should not be included in the models at this time. As well, the energy approach was shown by Aleshinsky to lack mathematical validity. The alternate method, a modified joint power approach (using absolute values), was shown to be mathematically valid (Aleshinsky, 1986), but has only be used in one study (Chapman, 1987) which had only one subject, and produced somewhat ambiguous results.

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APPENDIX B - SAMPLE CONSENT FORM

Information and Consent Form for the Study: Comparison of Methods for Calculating Internal Work of Ambulatory Human Movements in Elite Runners

Purpose and Benefits: The purpose of this research is to measure and compare two different methods for calculating internal work. These measures will help determine which model is the best for determining the efficiency of human movement. This information can be used to improve training and to evaluate pathological, elderly and possibly robotic movements.

Procedure: Anthropometric data (age, gender, height, weight, body segment lengths) will be collected. You may be asked to remove some clothing or to wear clothing appropriate for running: t-shirt or tank top and shorts or stretch pants, to which reflective markers will be attached. Markers will be placed on various joints. You will warm-up, including several practice runs, then run five trials at your chosen sub-maximal speed across a force platform. This will be followed by four trials of modified runs at the same speed. You will run 20 to 30 feet for each trial, and all trials will be filmed. The test will take at most two hours and will be completed in one session.

Risks: There is minimal risk involved in this experiment. The modified trials have been examined biomechanically to ensure that there is minimal physical risk. The subject may stop the experiment at any time for any reason.

Anonymity: Each subject will be assigned a code which will be used in any material presented or published.

In signing this consent form you acknowledge that you have read and understood the above statements. You enter the biomechanical investigation willingly and may withdraw AT ANY TIME without penalty or discrimination. Please be aware that you may report what you consider to be violations of your welfare to the Faculty of Health Sciences Human Research Ethics Committee.

I have read the above comments and wish to proceed with the biomechanical evaluation.

Date:____________________ Signature:____________________________________

Witness:____

I hereby consent to and authorize the use and reproduction of any and all photographs, videos or motion picture films taken of me during this biomechanical evaluation for scientific or research purposes, with the understanding that my identity will be kept confidential.

Date:____________________ Signature:____________________________________

Witness:____

Investigators:
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This study has been approved by:
Frank Reardon, Chair
Faculty of Health Sciences - Human Research Ethics Committee
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APPENDIX C - P VALUES

The following chart records the largest p value for each subject and whether this value is significantly different (SD) or not significantly different (NSD) than the mean normal run for that subject. If it is not significantly different, the next largest p value for that subject is recorded until a p value representing a significant difference occurs. All other p values are smaller than those recorded here.

Table 3: Each Subject's Largest P Value

SUBJECT	TYPE OF RUN	P VALUE
DA	Stiff Knees (SK)	0.00099 SD
QC	Stiff Knees (SK)	0.00059 SD
MJ	Overstriding (OS)	0.000214 SD
PJ	Exag. Arm Swing (EAS)	0.002264 SD
AO	Stiff Knees (SK)	4.38E-05 SD
DS	Stiff Knees (SK)	0.001095 SD
HO	Exag. Arm Swing (EAS)	0.03828 NSD
HO	Overstriding (OS)	0.002334 SD
VW	Exag. Arm Swing (EAS)	0.02607 NSD
VW	Stiff Knees (SK)	0.00086 SD