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Methods for calculating internal mechanical work: comparison using elite runners

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Abstract

Two methods for calculating internal work—the absolute work method, based on changes in mechanical energy, and the absolute power method, based on the powers produced by the joint moments of force—were compared. The results from both methods were normalized to body mass and running speed to obtain the 'internal biomechanical cost' (IBC). The IBCs of normal running for eight runners were compared to their IBCs for four inefficient running styles. The absolute power method was able to detect the inefficient runs significantly more often than the absolute work method ($\chi^2 = 3.22$, $P < 0.05$). In addition, the absolute power method showed less variability quantifying both internal and external work. In conclusion, the absolute power method was judged the superior technique for quantifying mechanical energy costs of running.

Keywords: Mechanical energy; Power; Inverse dynamics; Kinematics; Kinetics

1. 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. The traditional definition of work, also called external work, is not an effective measure because of the 'zero work paradox'. This paradox occurs whenever a body moves at constant velocity on a level surface (e.g. running on a level treadmill or pedaling a bike ergometer with no resistance) resulting in no external mechanical work done despite the reciprocating motions of the arms and legs [1]. 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 like arm swinging or head bobbing. We can determine the physiological cost by measuring oxygen uptake, but this does not give insight into any mechanical differences that may exist. For example, if runner 'A' has a lower cardiac capacity (max VO_2) than runner 'B', A's running style must be more mechanically efficient to win the race. To determine the mechanical differences in style we must know how much internal work the runner did.

Different computational models have been proposed to calculate internal mechanical cost [12,16]. Most of these models use the traditional approach of examining changes in segmental energies to estimate mechanical cost. An initial equation, called the pseudo-work equation, was developed by Norman et al. [9]. Winter [17] refined this equation so that the work was calculated for the total body, not just the segments, and also expanded the equation to include energy transfers within and between segments. This was called the internal work equation or W_{wb} (work done which permits transfers within and between segments). There have been attempts to modify this equation to incorporate other forms of energy transfer, such as elastic storage of energy in the tendons, but the values used have been arbitrary and no 'best' model has been found [14,15]. This approach has been applied in a number of studies examining a wide range of activities, including walking

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[11,17], running [16], cross-country skiing [8,10] and rowing [7]. For comparison purposes we therefore used a modified version of the W_{wb} equation in this study, which we termed 'absolute work'.

Unfortunately, the validity and reliability of this approach was never proven. There are two main points on which it falters—between segment energy transfers are always assumed to occur when segments move simultaneously and conservative movements are not correctly recognized. The following examples should help clarify these points (cf., Wells [14]). Negative work occurs when a person lowers an arm from a raised position. Positive work occurs when a person raises a leg from a lowered position. When these movements occur asynchronously, the internal work equations compute the work involved correctly. When these movements are performed simultaneously, however, the decrease in energy of the lowering limb is assumed to cause the increase in energy of the raising limb. Since between segment energy transfer is erroneously assumed to have occurred, the total body work is underestimated.

A different approach to calculating internal work that eliminates these problems uses inverse dynamics and joint power analysis [13]. This approach computes the powers produced by the moments of force at the joints then integrates them with respect to time to find the work done. Winter [18] outlined the principles underlying this method. Although Elftman [5] first described the basic equations in 1939, this method of determining work has not often been used, likely because a reliable device for measuring ground reaction forces was needed and the calculations are more complex. In Elftman's equations, positive and negative power values cancelled each other before they were integrated, therefore ignoring the internal mechanical work done. Aleshinsky [1] eliminated this problem by modifying the power equations so that the absolute values of the moment powers were summed to determine the total mechanical work (internal plus external work). He also established the validity of the moment power method and identified errors introduced by the energy approach. A version of Aleshinsky's equation was used in this study and was termed the 'absolute power' method.

Although the absolute work approach is mechanically invalid compared to the absolute power approach, very little research has been done to determine if there is a significant practical difference between the two methods. Chapman et al. [3] compared normal running with modified running styles that were considered inefficient, to see if differences could be distinguished. Unfortunately, this study had only one subject and compared total work values without accounting for the external work done. Caldwell and Forrester [2] also compared the power and energy approaches. Their study also had only one subject and focused on comparing energy transfers across joints only during the swing phase (since no force platform was used). These studies tested the principles outlined by Aleshinsky but with only single subjects, no statistical comparisons could be made.

1.1. Purpose

Similar to Chapman's protocol [3], inefficient types of running were compared to efficient running to determine which computational approach was better able to detect the mechanically inefficient runs. Internal work, calculated using both the absolute power approach and the absolute work approach, was divided by the running velocity and body mass to obtain the 'internal biomechanical cost' (denoted IBC). The IBC for the mean normal run (considered the efficient style) was statistically compared to IBC values of each of the modified runs (inefficient styles) for each of the four male and four female elite runners. The number of times the inefficient runs were significantly different from the normal runs was then compared for the two approaches.

1.2. Methodology

The subjects used were middle distance or cross-country runners, with a minimum of 2 years of training and competition. There were four females and four males, all above 18 years of age. Informed written consent was obtained from each person prior to participation. Age, gender, height, weight and various segment lengths of each subject were recorded.

Twenty-one markers were placed over the approximate joint centers of the twelve segments (head-neck, trunk, 2 forearms, 2 arms, 2 thighs, 2 legs and 2 feet). To reduce the risk of injury, subjects did a warm-up including several practice runs. They were then filmed at 100 frames per second (Locam cinecamera) as they ran across an inlaid force platform (Kistler). The coordinate data were digitized, refined by a fractional linear transformation (2D version of a DLT) and filtered by a Butterworth low-pass filter [19]. The accuracy of each trial was evaluated by comparing the actual locations of known coordinates with their digitized and scaled coordinates. In all trials, accuracies of 0.5 mm or better were achieved.

The ground reaction forces were sampled at 200 Hz. Each subject did five trials of normal running at their self-selected pace followed by one trial each of four modified runs. The modified runs were: exaggerated knee flexion (EKF), over-striding (OS), stiff knees and exaggerated arm-swing (EAS), (cf., Chapman et al. [3]).

Practice of each of the modified runs occurred after a verbal description and physical demonstration, with the goal being to run in an exaggerated fashion while still maintaining accuracy in hitting the force plate. Only one trial of each modified run was recorded due to the difficulty of replicating these novel running patterns.

The digitized coordinate data were then synchronized with the force platform data using custom software (Biomech Motion Analysis System http://www.health.uottawa.ca/biomech/csb/software). 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, instead of a full stride. It was assumed that the runners were bilaterally symmetric.

Two-dimensional segmental kinematics and inverse dynamics were then used to calculate the net moments of forces at the eleven joints [19]. From these internal and external works were calculated using the two different approaches. One method used the changes in segmental energy to calculate internal and external work [19]. The other used the integration of joint powers to calculate internal and external work [1].

1.3. External work

When calculating external work the absolute work approach sums the segmental energy changes over the movement cycle. This is equivalent to subtracting the initial total body energy from the final total body energy.

$$W_{\text{ext}} = \sum_{i=1}^{N} \left[\Delta \sum_{s=1}^{S} E_{si} \right] = \sum_{i=1}^{N} \Delta E_T = E_{T_N} - E_{T_0}$$

W_{ext}, external work as calculated by the segmental energy method; N, number of frames in the cycle of motion; S, number of body segments; E_{si}, energy of segment s at time i; E_{T_N}, final total body energy; E_{T_0}, initial total body energy.

For the absolute power approach, external work was computed as the sum of the moment powers over the motion cycle (time), where moment power is the product of the net moment at a joint times the joint's angular velocity.

$$W'_{\text{ext}} = \sum_{i=1}^{N} \sum_{j=1}^{J} P_{ij} \Delta t = \sum_{i=1}^{N} \sum_{j=1}^{J} (M_{ij} \omega_{ij}) \Delta t$$

W'_{ext}, external work as calculated by the moment power method; P_{ij}, moment power of joint j at time i; M_{ij}, net moment of force at joint j and time i; ω_j, joint angular velocity; Δt, sampling time = 1/100 s; J, number of joints.

1.4. Internal work

Internal work cannot be determined directly so instead, total mechanical work is computed and then the external work done is subtracted yielding the internal work. The approach based on computing segmental energies sums the absolute values of the changes in total body mechanical energy over a movement cycle (called W_{wb} [19]) then subtracts the external work done (cf., Pierrynowski et al. [12]). For this method, the energy-based external work was subtracted (W_{ext}) and the resulting value was called the absolute work. The other approach [1] based on the net moments of force, sums the absolute values of the powers produced by the moments of force and then subtracts the external work. For this approach, the power-based external work (W'_{ext}) was subtracted and the resulting value was called the absolute power. The two internal work equations are as follows:

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

$$\text{Absolute power} = \sum_{i=1}^{N} \sum_{j=1}^{J} |P_{ij}| \Delta t - W'_{\text{ext}}$$

1.5. Internal biomechanical cost and statistics

To reduce the risk of injury when the subjects performed the modified (inefficient) runs their velocities were not controlled but the subjects were requested to run at approximately the same speeds as their normal running trials. For an accurate comparison of the normal and modified runs, the internal work values were normalized by dividing by the running velocity. Before comparisons among subjects could be made internal work was also divided by body mass. The resulting values were termed the IBCs.

$$\text{IBC} = \text{internal work}/(\text{running velocity} \times \text{body mass})$$

For each method, (absolute work and absolute power) each subject's IBC values for the normal runs were averaged to obtain a mean normal run. This was then compared to the IBC values for each of their modified runs using a planned comparison with a Bonferroni corrected alpha level of 0.0125. The results were then compared between the two approaches to determine which computational approach was better at detecting the inefficient runs. Since Aleshinsky [1] showed that the energy-based equations were not valid, it was expected that the absolute power approach would detect a greater number of inefficient runs. A one-tailed χ^2-test was then used to determine if the number of inefficient runs detected was significantly different for the two computational methods [6].

2. Results

Eight subjects performed five normal runs and four modified runs each. The IBCs of the mean normal run and the four modified runs for each subject are shown in

Table 1
IBCs (J/(kg m/s)) for normal and modified running styles

Subjects	Absolute work					Absolute power				
	Mean normal	EKF	OS	SK	EAS	Mean normal	EKF	OS	SK	EAS
Female 1	0.61	1.46^{a}	2.41^{a}	1.42^{a}	1.74^{a}	1.26	1.78^{a}	1.81^{a}	1.60^{a}	1.71^{a}
Female 2	1.59	2.32	2.64^{a}	1.52	1.15	1.08	1.62^{a}	1.97^{a}	1.37^{a}	1.11
Female 3	0.66	2.25^{a}	1.89^{a}	2.72^{a}	0.79	1.22	2.63^{a}	1.67	2.09^{a}	1.10
Female 4	0.38	1.08^{a}	1.40^{a}	0.64	0.82^{a}	1.26	2.12^{a}	2.24^{a}	1.67^{a}	1.53^{a}
Male 1	1.99	0.47^{b}	1.67	1.39	1.88	1.46	1.82	1.85	1.47	1.46
Male 2	1.31	1.07	1.26	1.17	0.63^{b}	1.10	2.54^{a}	1.47^{a}	1.28	1.30
Male 3	1.10	3.36^{a}	2.79^{a}	1.92^{a}	2.03^{a}	1.39	3.26^{a}	3.59^{a}	1.58^{a}	1.72^{a}
Male 4	1.31	1.52	1.33	1.50	2.24^{a}	1.20	2.61^{a}	1.75^{a}	2.37^{a}	1.90^{a}

[a] Significant difference between the mean normal run and the modified run.
[b] Modified run was significantly less than the mean normal run.

Table 1. There was no significant correlation [4] ($r = 0.128$, $P = 0.763$) between the two methods of computing the IBCs for the mean normal runs. However, there were differences between the IBCs for the normal running trials and the modified runs. Each modified run that was significantly different from the mean normal run is marked with a superscript ‘a’ or ‘b’ in Table 1. For the absolute power method, 23 of the 32 modified runs were detected as having significantly higher energy costs—a 72% detection rate. In no case did a modified run yield lower cost than the normal running trial.

For the absolute work method, only 16 of the 32 modified runs (50%) showed significantly more work than the normal runs. Furthermore, nine modified runs showed less work than the normal running style, however, only two of these were significantly different. Since it was unlikely that a modified run was more efficient than the normal running style, these should be considered erroneous results. Comparing the two techniques, detection of inefficient runs was significantly better for the absolute power method versus the absolute work method ($\chi^2 = 3.22$, df = 1, $P < 0.05$).

As seen in Table 1, the modified running style with the lowest cost was most often that of EAS. This occurred even though all subjects performed extremely exaggerated arm swings. The implication of this result is that during normal distance running an arm-swing that is only slightly exaggerated will have very little effect on the total amount of work done.

As seen in Fig. 1, the type of modified run was important in detecting differences for the absolute power method, but not for the absolute work method. If the EAS runs are ignored, absolute power method detected 19 of the 27 inefficient runs (79%). Absolute work was not consistent in the type of modified runs that it could detect, although it generally performed better with OS. It was able to detect the differences in all four modified runs for only two of the eight subjects.

Fig. 2 shows the IBC of the mean normal run for both calculation methods. The error bars represent the standard error. Of note are the magnitudes of the standard errors, the absolute work standard errors were approximately twice as large as those of the absolute power method.

Fig. 3 shows the external work for normal running. The external work values for absolute power should theoretically be equal to the external work values of absolute work, but this is obviously not the case. During normal running, using the absolute power method (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 eight 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. Only one of the external work values for the absolute power method exceeded 90 J during normal running.

Using the absolute work method (diamonds), four of the subjects were speeding up and the rest of the subjects had values that varied. In addition to being more variable, the values for absolute work were often greater than the absolute power values.

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 Section 1.2, 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.

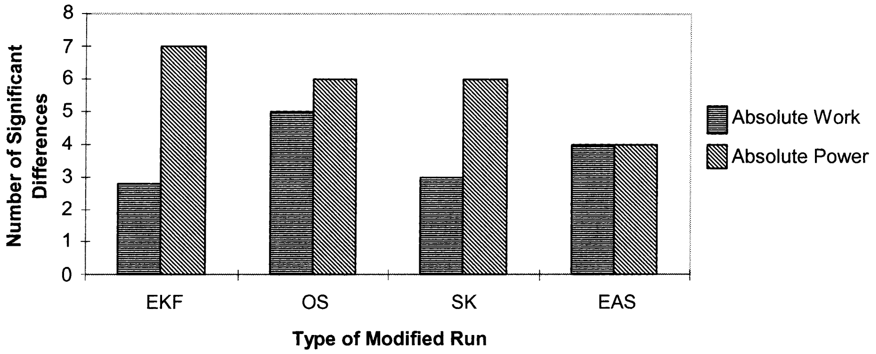

Fig. 1. Number of modified runs with significantly greater IBC than normal runs.

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 (46.8%) 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. Either arm did little work with the greatest amount being 2.6%. 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 supposition that arm-swing is a relatively unimportant aspect of running style for distance running. Two other results were of note. External work was only 9% of the total and the upper body contributed only minimally.

3. Discussion

There were several differences between the two calculation methods that have practical significance. Internal work calculated using the absolute work approach had larger standard errors than for the absolute power method, denoting greater variability for the absolute work method. External work calculated using the absolute work approach also showed greater variability than the absolute power approach. In addition, two modified runs had lower IBC values than their normal runs with the absolute work method, indicating large errors. The greater variability of the absolute work method indicates reduced reliability. This is confirmed by the absolute work method detecting significantly fewer of the inefficient runs than the absolute power method.

Chapman's et al. [3] single subject study compared normal running to four inefficient runs. Total work values (internal and external work combined) were calculated using the energy and power approaches. For the energy approach the normal run was more work than three of the four inefficient runs whereas for the power method the normal run was less work than three of the four inefficient runs.

Caldwell and Forrester [2] also conducted a single subject study comparing power and energy approaches. They did not use a force platform, but compared work and energy transfer estimates across the joints of the recovery leg during walking and running. They found that the energy method underestimated the work 'due to

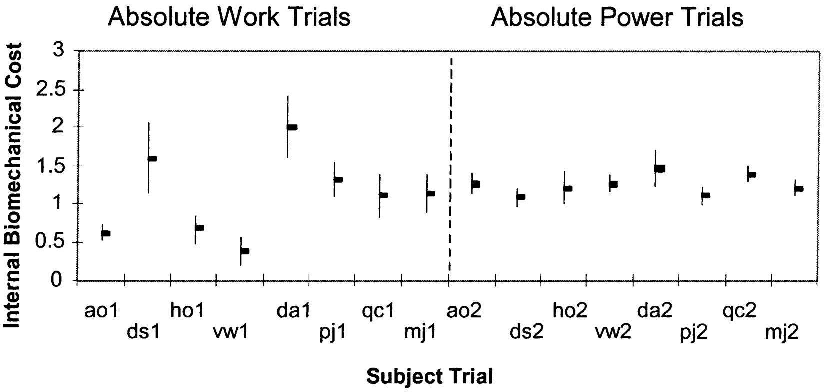

Fig. 2. Comparison of the international biomechanical cost (J/(kg m/s)) of the mean normal runs as computed by the two mathematical methods.

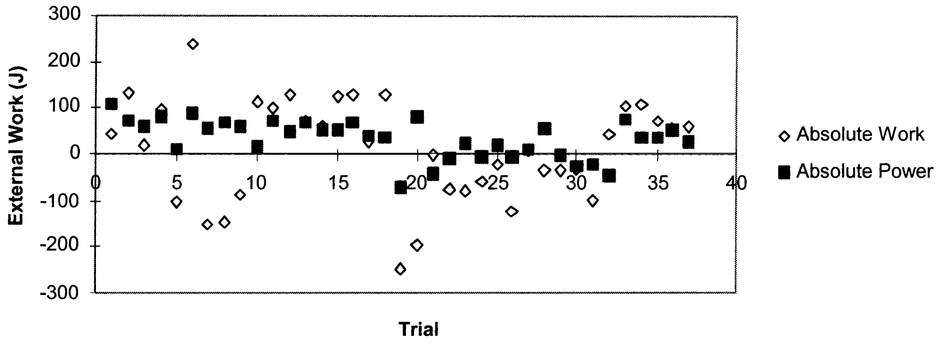

Fig. 3. Comparison of the external work of normal as determined by the two methods.

Table 2
Positive and negative work as a percentage of total work

Joint	% Positive	% Negative
Rt. ankle	14.0	5.3
Rt. knee	6.7	14.1
Rt. hip	14.0	10.2
Lt. ankle	0.5	0.1
Lt. knee	0.3	9.6
Lt. hip	12.6	3.1
Rt. elbow	0.5	0.2
Rt. shoulder	2.1	2.0
Lt. elbow	0.7	0.7
Lt. shoulder	1.7	1.6
Rt. lower extremity	34.7	29.6
Lt. lower extremity	13.4	12.7
Rt. upper extremity	2.6	2.2
Lt. upper extremity	2.5	2.3
Total body	53.2	46.8

muscle powers at joints opposing each other in energy generation and absorption'. For the power method, four energy transfer mechanisms were identified and their relative importance through the swing phase described.

Both of these studies used one subject to test the principle presented by Aleshinsky [1] that errors in the energy method lead to an underestimation of the work being done; and that the power approach is better because it takes into account both positive and negative work. The results of both these studies support this principle. A broader examination using more than two subjects was needed to see how far this principle holds. This study, which used eight subjects to compare thirty-two modified runs to normal runs, fulfilled this need.

This study has demonstrated a significant practical difference between the absolute work method (energy approach) and absolute power method (power approach). The absolute power method, however, was not able to detect all inefficient runs. There are several possible reasons for this—the types of movements chosen and limitations in our model.

The absolute power method had high rates of detection (72%) for all movements except EAS (50%). There are two factors that likely contributing to this: the small amount that the arm-swing contributes to the total work; and the sensitivity of the absolute power approach. As seen in Table 2, the arm-swing only contributes about 2.5% per arm to the total work done. Even assuming this amount doubles with EAS, this is still not a large amount. At this point, the sensitivity of the absolute power approach has not been fully investigated, but a 2.5% difference might not be distinguishable from measurement error.

Each method has its limitations. For instance, neither can measure several biological factors, including the presence of two-joint muscles, antagonist co-contractions and elastic storage of energy [1,2,14,16].These factors were present to some unknown extent in the movements performed in this study. Since they cannot be quantified, they add to the variability of the results. This is especially true if they play a larger role for one type of movement than for another (i.e. inefficient vs. normal runs).

Despite these limitations, we found that the absolute power method was better at detecting gait inefficiencies than the absolute work method. In 1986, Aleshinsky [1] described the validity of the two methods, the principle was tested by Chapman et al. [3] and Caldwell and Forrester [2] and now the practical difference between the two methods has been demonstrated.

The absolute power approach is also analytically superior because it can determine energy generation, dissipation and transfer in detail. Coaches and therapists can use both simple movement analysis Table 2 and complex movement analysis (Caldwell and Forrester [2]) 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 this 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.

4. Conclusion

The absolute power method was sensitive enough to detect the inefficient modified run significantly more often than the absolute work method. In addition to detecting mechanical inefficiency more frequently, the absolute power method was demonstrably more reliable in two other ways—the standard error was half the standard error of the absolute work method and the external work was less variable and closer to zero than absolute work method. Furthermore, the absolute power method can quantify the energy transfers at joints and which joint moment generates or dissipates energy. It is therefore recommended that the absolute power method be used whenever possible to quantify total or internal mechanical work, i.e., whenever moments of force can be computed. The absolute energy method should only be used when it is not feasible to quantify the net moments of force, for example, when ground reaction forces are unmeasurable.

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