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Contrast of Methods for Calculating Internal Work of Running for Trained and Untrained Runners

Thesis submitted to the School of Graduate Studies and Research in partial fulfilment of the requirements for Masters of Science degree in Human Kinetics

University of Ottawa

Patricia A. Turnbull

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Abstract

This research contrasted two methods for calculating the internal work of running. The methods are known as absolute work (also known as Winter's (1979) W_{wb} calculation) and absolute power. The study also examined whether or not there were differences in the amounts of internal work done by trained and untrained runners. The absolute work approach was believed to calculate internal work incorrectly. The absolute power approach, on the other hand, correctly computes internal work by taking the absolute power generated or absorbed at each joint and summing them across a movement cycle.

Five trained and five untrained female runners were filmed, while running across a laboratory runway, by a cinecamera at 100 fps. Simultaneously, force plate data, for one step, were collected. The results showed absolute work values were three times the absolute power values. Furthermore, the results of the absolute work method were too large compared to the estimated physiological cost of running. Conversely, the absolute power method produced amounts of internal work that were too high but were much closer to the estimated physiological cost. There was no significant difference between work values of the two groups of runners, for the absolute power method. The correlations for the absolute power method were higher than those of the absolute work method. Based on the results, the absolute power method provided a more accurate estimate of locomotor cost of running.

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Introduction

In athletic events, often there is a very slight margin of victory for one athlete over another. The question can be posed—was the victorious athlete the more efficient or just the better endowed? The problem of efficiency of human movement is complex. The first question to be asked is how does one quantify efficiency? Winter (1978) defined work efficiency and mechanical efficiency in his extensive review of the topic. In this study the term that is of most interest is mechanical efficiency. It is defined as the ratio of the total work done to the physiological cost (Winter, 1978). Total work includes internal and external work. Internal work is the work required to move the body segments through a cyclic movement while external work is the work done by the body on an external load or the body's mass (Winter, 1978). The physiological cost is usually measured indirectly from oxygen uptake.

Historically, there are two routes to calculating work done. They are the energy approach (Wells, 1988), and the power approach (Elftman, 1939). The energy approach uses segmental energies calculated from kinematic data; whereas, the power approach uses the moments of forces calculated by inverse dynamics to determine work. The energy approach has been most widely concentrated on in past studies. Initially with this approach, total body work was calculated without regard to savings of energy produced by transfers of energy between and within segments (Fenn, 1934; Norman et al., 1976). Fortunately, this method of

calculating work was recognized as overestimating the actual work done. Later Pierrynowski and his colleagues (1980) modified these work equations and came up with equations that calculated total work and total work taking into account transfers of energy between and within segments. The latter equation was termed W_{wb} or the internal work equation (Winter, 1979). This approach is referred to in this study as the absolute work approach. The equation sums the absolute values of the changes in the total body's mechanical energy over the time period and then subtracts the external work performed during that time period to calculate internal work.

$$W_{wb} = \left(\sum_{k=1}^N |\Delta E_{b_k}| \right) - \left(\sum_{k=1}^N \Delta E_{b_k} \right)$$

This equation and approach was not regarded by all as a correct way of dealing with the calculation of internal work. The absolute work approach was criticized by investigators such as Aleshinsky (1986). He stated that when movements of equal magnitude but opposite direction occur simultaneously, the work done by the two movements cancel. A simple example will illustrate this situation. An individual raises one arm while lowering the other arm at exactly the same time. In the absolute work approach the resultant value shows that no internal work has been done. It is assumed that the energy is transferred from one arm to the other. It is obvious that this is not true. Energy was not transferred—positive work raised one arm and negative work lowered the other arm. The negative work of one movement has cancelled out the positive work of the other movement.

Other investigators (Chapman et al., 1987; Wells, 1988; Caldwell and Forrester, 1992) also recognized this weakness in the absolute work approach and considered the power approach as a viable alternative. The power approach sums all of the powers produced by the moments of force at each joint over the whole time period. The power is calculated by taking the time integral of the products of the joint moments and the joint angular velocities.

Investigators such as Aleshinsky (1986) and Chapman et al. (1987), working independently, re-visited the foundations of the power approach and found flaws with it. Chapman noted that the internal work calculated via the power method will not include cost to muscles at joints that show an equal but opposite magnitude of power. If the elbow shows a generation of power while at the same time the wrist shows an absorption of power, the overlapping powers will cancel each other out. Thus, the internal work will be underestimated.

To try and correct for the problems cited in the absolute work approach and power approach equations a new approach to calculate work was developed. This approach was examined mathematically by Aleshinsky (1986) and studied empirically by Chapman et al. (1987) and Caldwell and Forrester (1992). This will be called absolute power approach. Instead of adding the powers directly as in the conventional power, the absolute power equation sums the absolute value of the powers produced at each joint and then sums them across the number of samples and subtracts the external work.

$$W_{i_{abs\ power}} = \left(\sum_{k=1}^N \sum_{j=1}^J |M_{j_k} \omega_{j_k} \Delta t| \right) - \left(\sum_{k=1}^N \sum_{j=1}^J (M_{j_k} \omega_{j_k} \Delta t) \right)$$

The absolute power approach solves the problems encountered by the absolute work approach and the conventional power approach by taking the absolute power at each joint. Thus, it accounts for every generation (positive work) or absorption (negative work) of mechanical power at every joint. This will give a more realistic value for the internal work done than the other methods.

During these initial stages of development of the work problem, investigators still attempted to calculate efficiency. Unfortunately there is an inherent problem with the type of ratio they were using. The first part of the ratio uses biomechanical measures of work while the second part uses physiological measures of cost. Since physiological measures of oxygen uptake are indirect, there is a time delay from when the oxygen is used by the muscles until its output as carbon dioxide at the mouth. Thus, valid physiological measures cannot be taken over short time periods. This means to get an accurate measure of the oxygen uptake the subject must be in a steady state for several seconds. Unfortunately, biomechanical measures are usually only possible for small durations of time or single movement cycles due to the large volume of data that must be collected. Therefore, this type of ratio is not ideal for a biomechanical study. A more suitable ratio for this study would include total work over speed of movement. In running, the numerator would be internal work plus external work and the denominator would simply be running speed. The current subjects ran on level ground at constant velocity so the external work for each cycle was zero. Therefore, the mechanical work reduced to the internal work over the running speed. The internal work was also divided by the subject's body mass to permit comparisons across subjects. This value will be called the internal biomechanical cost (IBC).

The calculation of work using any available method has many variables that cannot be accounted for in existing equations. According to Williams and Cavanagh (1983), there are three major sources of mechanical power. The first source is the power generated by the muscles that cross the joint of interest. The problem of calculating work with this power is that the energy expended depends on whether the contraction is eccentric or concentric. It is well known that an eccentric contraction (negative work) will have a much lower physiological cost than a concentric contraction (positive work). Unfortunately, the mechanisms behind this difference in physiological cost are not fully understood. The exact ratio of physiological cost that exists between the two types of contractions is unknown and has been experimentally defined as anywhere from 1:2 to 1:6 (Abbott and Bigland, 1953; Passmore and Durnin, 1955; Magh et al., 1965; Margaria, 1968; Norman et al., 1976). Since it is biomechanical cost and not physiological cost that is being addressed in this study, this perceived problem does not exist. One joule of negative work equals one joule of positive work when viewed from a mechanical perspective (Caldwell and Forrester, 1992). This is also reflected in the absolute power equation (Caldwell and Forrester, 1992), where it is the mechanical work that is being calculated not the physiological work. Thus, the concentric to eccentric work ratio must be 1:1.

The second source of mechanical power comes from the storage and release of elastic energy (Cavagna et al., 1964, 1968, 1971; Asmussen and Bonde-Petersen, 1974; Cavagna et al., 1977). There is no way of measuring this stored energy in an intact human. In a machine, stored energy comes in the form of a spring. Each spring has an empirically or mathematically determined spring constant. For humans, however, we cannot take the muscle

out to determine its spring constant. Even if one could do this, the amount of stored energy in a muscle may depend on a number of factors, such as, the velocity of eccentric contraction (Funato et al., 1985), fibre type, fibre arrangement and mechanisms in the crossbridge phenomenon (Aura and Komi, 1987).

The third source of mechanical power according to the above authors is due to the transfers of energy between segments. These transfers can be via muscles, ligaments or direct bone-on-bone contact. The power equations must be adjusted to account for all of these sources. The lack of conclusive information regarding these sources of energy, makes it difficult to define work or energy formulas that accurately reflect the state of affairs (Williams, 1985).

Other limitations to these types of models involve the assumption that the muscles at the joint are single equivalent muscles. This prevents indeterminacy, however, cocontractions at the joint of interest cannot be analyzed because the individual muscle powers cannot be dissected into their component parts; thus, an underestimation of the work done occurs. Also, two-joint muscles are difficult to model. Wells (1988) has suggested that active two-joint muscles can offer a savings of work over a series of one-joint muscle systems. Wells went further and developed an algorithm that demonstrated how energy costs can be divided between two-joint and one-joint muscles.

The last limitation associated with this type of analysis is the assumption that certain joints are frictionless pin connections and that the body is composed of rigid segments. This is a simplification. Thus, energy dissipated due to deforming the tissues will not be accounted for in the model. Robertson and Winter (1980) in their study found that these assumptions were

valid for walking. These assumptions, however, may not hold for running. Walking optimizes energy costs, whereas running may not have that as a goal.

Even if a perfect model was defined, there would still be the problem of defining what is optimal IBC and, thus, what is the minimum amount of work that must be done for certain movements. The body may require certain cocontractions to operate safely or may only be able to use a certain amount of stored energy. When performing maximal movements that require the full ranges of motion, such as in sprinting, the body naturally activates antagonistic muscles in an attempt to prevent injury. The type of running performed in this study did not require the full ranges of motion, so this type of cocontraction was not necessary.

Purpose

The purpose of this study was to contrast the absolute work and the absolute power approaches for measuring internal mechanical work. It was also to test whether the absolute power method could distinguish differences in the internal biomechanical cost (IBC) of running between trained and untrained runners. This improved method will assist a coach in training an athlete to achieve his/her best results on a consistent basis. When training athletes for endurance events, coaches can eliminate inefficient movements and decrease the cost of the activity to the athlete. Clinicians may also be able to use this methodology to identify inefficiencies in people with gait pathologies such as cerebral palsy or Parkinson's disease. Treatments can then be tested to see if the inefficient movements are lessened in these patients.

Methodology

In this study two internal work equations and two external work equations were used to assess the IBC of trained and untrained runners. Each subject ran at a submaximal level several times. IBC was calculated by dividing the amount of internal work done by the subject's mass and by the speed of running. Both types of work were measured using the energy equations and power equations. The absolute work based external work is the sum of all the kinetic and potential energies of each segment over the cycle of motion. The absolute power based external work is the integral of the sum of the powers at each joint over the period of the cycle. In this study the external work should equal zero. The internal work, based on the absolute work approach is the absolute values of the changes in total body energy summed over the entire cycle minus the external work. The internal work using the absolute power based equations, is calculated by summing the absolute values of each instantaneous power at each joint and then summing them across the duration of a cycle and then subtracting the external work.

Subjects

Five female varsity level middle distance runners with at least one season of training at the varsity level and five female untrained runners (no running experience) were chosen for the study. The trained runners were recruited either individually or through their varsity coach.

The untrained runners were volunteers from the general population. Subject ages ranged from 14 years to 30 years. All subjects were interviewed for running history to ensure they fit well within the boundaries of each category.

Apparatus

A 16 mm cine camera (Locam) was used to film the subjects as they ran. A force plate (Kistler) was used to record ground reaction forces from each trial. BIOWARE 2.11 (Kistler) software was used in conjunction with the force plate for force collection purposes. Digitizing of each trial was done with the use of a digitizer (Hewlett Packard 9874A) and a motion analyzer (LW Motion Analyzer). The DigFix (Biomechanics Laboratory, University of Ottawa) software program was used to examine the digitized images and correct digitizing errors. The BIOMECH (University of Ottawa) package was used to process and analyze the digitized film and compute joint and segmental kinematics. The BIOMECH software programs use inverse dynamics to calculate net forces and moments. The ENERGY and FORCE (Biomechanics Laboratory, University of Ottawa) programs were used to calculate internal work and external work by both the energy and the power approaches, respectively.

Protocol

Subject setup. Each subject read and signed a consent form. Subjects then had markers placed on their right lateral aspect of the shoulder, elbow, hip, knee and ankle. Markers were also placed on the subject's shoe at the heel, ball and last toe (fifth metatarsal). Another set of markers were placed on the subject's left medial aspect of her elbow, knee, ankle, heel, ball

and first toe (first metatarsal). Subjects warmed-up; novice runners were given instructions on warming up procedures.

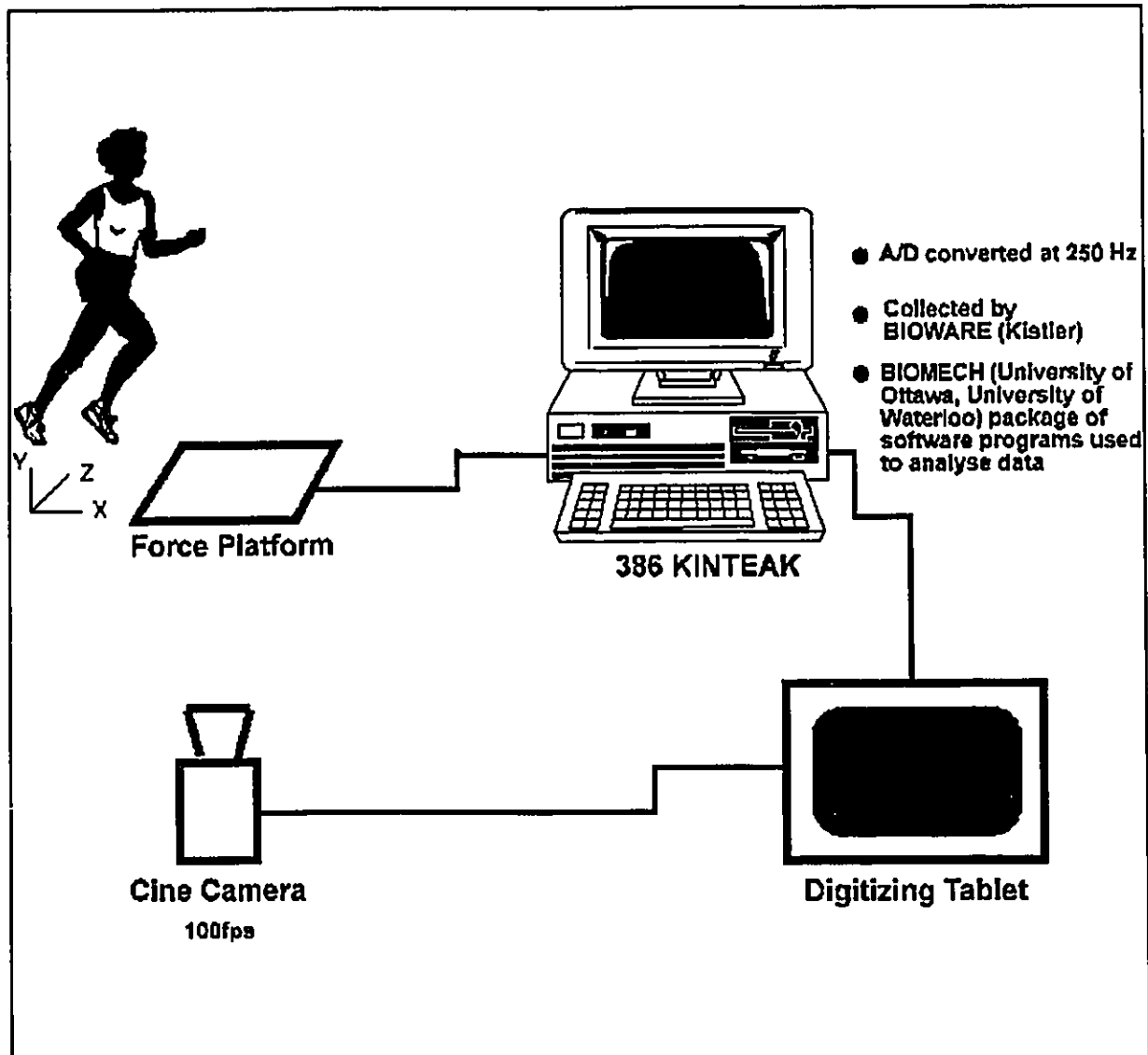


Figure 1: Setup for data collection and reduction.

Data collection. The subjects were asked to run at a speed comfortable to them.

Practice runs were performed so each subject's running speed could be set close to the target speed. After the practice runs, each subject ran across the force plate while film and force data

were collected at 100 fps and 250 Hz, respectively. Each subject performed five good trials with as many rest breaks as necessary.

Design. This study was concerned with whether or not the new absolute power method is a sensitive enough tool to determine differences in IBC between groups. IBC from that method were compared between the two groups using an independent groups, directional, t-test ($p < 0.05$). A directional t-test was employed because it was assumed that the trained runners would demonstrate lower IBCs than the untrained runners. The absolute work IBC results were compared through correlation. The external work values were compared only to see if errors arose due to synchronizing the film with the force plate, assumptions such as rigid bodies and pin connections, phasing in a cycle (the end of a cycle was not captured on film due to sampling) or from the subject speeding up during the cycle. In this design external work is theoretically zero. Thus, to be consistent with this assumption, any non-zero value of external work was subtracted from the total work to obtain the internal work.

Data reduction and analysis. An independent t-test was used to compare running speeds of the two groups. The filmed images and the force plate data were synchronized by visual inspection of the data. The heel-contact of the ipsilateral foot was matched with the first vertical force datum over 25 newtons. The force plate data were resampled to match up with the film frames. The data were then processed by the BIOMECH package of software programs. Body markers were filtered at 10 hertz and forces were filtered with a cutoff frequency of 25 hertz. These filtered data were used in the energy and power equations (see below) to determine external and internal work.

IBC was then calculated by dividing internal work by the speed of running and the mass of the subject. This was done for both methods and for all trials. Averages of IBC for each method and each subject were determined. A qualitative analysis was done to compare the absolute power values to the absolute work values. A directional t-test ($p < 0.05$) was used to determine statistical significance between trained and untrained runners for the absolute power approach only.

External Work Equations

1) Absolute Work Approach (Winter, 1979)

$$E_{i_k} = PE_{i_k} + KE_{i_k} + RE_{i_k}$$

where E_{i_k} is the energy level of the i^{th} segment during the k^{th} sample period (frame), PE is the potential energy, KE is the translational kinetic energy and RE is the rotational kinetic energy of each segment.

$$E_{b_k} = \sum_{i=1}^S E_{i_k}$$

where E_{b_k} is the total body energy during the k^{th} sample period (frame) and S is the number of body segments.

$$W_{\text{ext}} = \sum_{k=1}^N (\Delta E_{b_k}) = E_{b_N} - E_{b_0}$$

where W_{ext} is the total external work done over N sample periods.

2) Absolute Power Approach

$$W'_{ext} = \sum_{j=1}^J \int M_j \omega_j dt$$

where W'_{ext} is the total external work done over N sample periods calculated using trapezoidal integration, J is the number of joints, M is the joint moment and ω is the angular velocity of the joint.

Internal Work Equations

1) Absolute Work Approach (Winter, 1979)

$$W_{wb} = \left(\sum_{k=1}^N |\Delta E_{b_k}| \right) - W'_e$$

where W_{wb} is the total internal work done over N sample periods.

2) Absolute Power Approach (Chapman, 1987)

$$W_i = \left(\sum_{k=1}^N \sum_{j=1}^J |M_{j_k} \omega_{j_k} \Delta t| \right) - W'_{ext}$$

where W_i is the total internal work done over N sample periods for J joints.

Results

Overall Results — Both Methods

The population averages of the IBC from the two groups and methods can be seen in tables 1 to 4. The range of speeds for the trained runners (group 1) was 5.51 m/s to 7.24 m/s ($X=6.26$ m/s). The range of speeds for the untrained runners (group 2) was 4.63 m/s to 8.02 m/s ($X=5.63$ m/s). After conducting a two-tailed, independent groups t-test, it was found that there was a significant difference between speeds of the two groups $t=2.285$ ($p<0.05$). The standard deviations and the coefficients of variation show the variability of the scores. The standard deviations and coefficients of variation of running speed for the trained and untrained runners are $s=0.547$, $c.v=0.087$ and $s=0.932$, $c.v=0.162$, respectively.

It was also interesting to note that the overall average internal work was lower, according to both methods, for untrained runners compared to trained runners, however, the IBC did not indicate this trend. The average IBC for trained runners in the absolute work approach was 4.39 (J/kg)/(m/s) and for untrained runners was 4.01 (J/kg)/(m/s), but, the absolute power method showed the reverse situation. The IBC for untrained runners [1.47 (J/kg)/(m/s)] was higher than the cost for trained runners [1.39 (J/kg)/(m/s)]. The IBC average value for the absolute work approach was approximately three times the value calculated by the absolute power approach.

Table 1: Average absolute work method results for trained runners.

Subjects	Mass (kg)	Speed (m/s)	Int. Work (J)	Int. Work/Mass (J/kg)	IBC (J/kg)/(m/s)	C.V. (%)
RNDS	52.0	5.72	1942.46	37.84	6.55	21.5
RNAO	59.1	7.12	1415.92	23.96	3.37	15.1
RNVW	49.1	5.74	1135.31	23.12	4.03	27.7
RNLH	61.7	6.41	1949.08	31.59	4.94	10.3
RNHO	65.8	6.33	1133.68	17.23	2.74	24.8
POP.AVG.	57.5	6.26	1531.19	27.04	4.39	21.9

Table 2: Average absolute work method results for untrained runners.

Subjects	Mass (kg)	Speed (m/s)	Int. Work (J)	Int. Work/Mass (J/kg)	IBC (J/kg)/(m/s)	C.V. (%)
RNHM	67.7	5.55	1662.68	24.56	4.44	15.2
RNSC	55.5	5.26	1171.55	21.11	4.01	18.2
RNYL	53.9	7.35	1581.87	29.35	3.95	25.6
RNFT	51.8	4.82	895.68	17.29	3.59	31.3
RNSA	71.8	5.16	1497.45	20.86	4.05	24.5
POP. AVG.	60.1	5.63	1361.85	22.63	4.01	40.2

Table 3: Average absolute power method results for trained runners.

Subjects	Mass (kg)	Speed (m/s)	Int. Work (J)	Int. Work/Mass (J/kg)	IBC (J/kg)/(m/s)	C.V. (%)
RNDS	52.0	5.72	356.0	6.85	1.21	7.8
RNAO	59.1	7.12	602.9	10.44	1.43	8.1
RNVW	49.1	5.74	384.5	7.83	1.36	4.6
RNLH	61.7	6.41	638.8	11.05	1.72	16.4
RNHO	65.8	6.33	467.1	7.10	1.12	14.2
POP. AVG.	57.5	6.26	506.1	8.75	1.39	19.0

Table 4: Average absolute power method results for untrained runners.

Subjects	Mass (kg)	Speed (m/s)	Internal Work (J)	Int. Work/Mass (J/kg)	IBC (J/kg)/(m/s)	C.V. (%)
RNHM	67.7	5.55	603.5	8.51	1.61	13.8
RNSC	55.5	5.26	413.3	7.26	1.42	7.6
RNYL	53.9	7.35	645.4	12.05	1.63	6.9
RNFT	51.8	4.82	350.2	6.76	1.41	4.5
RNSA	71.8	5.16	448.4	6.24	1.19	9.8
POP.AVG.	60.1	5.63	507.0	8.50	1.47	14.9

Absolute Power Results

Some individual subject trials were not included. It was determined, after careful analysis of their force plate signatures that transients occurred in these trials during data collection. This situation had no effect on the absolute work results for these trials.

A directional, independent groups t-test was performed on the absolute power results. It compared trained and untrained runners' IBCs. There was no significant difference found between the two groups $t=1.054$ ($p > 0.025$). Since there was no difference between groups, the data were pooled. Table 5 shows the correlational relationships of the pooled data that existed among various variables in this study. It also includes speed squared value correlations.

Table 5: Pearson correlation matrix for absolute power results.

	Speed	Work/kg	Work	Work/spd	Work/kg/spd	Mass
Work/kg	0.738					
Work	0.642	0.911				
Work/spd	0.159	0.661	0.856			
Work/kg/Spd	0.250	0.834	0.793	0.834		
Mass	-0.060	-0.076	0.333	0.503	-0.050	
Speed ²	0.997	0.740	0.634	0.149	0.253	-0.081

Absolute Work Results

The absolute work results were compared between untrained and trained runners for variability and within groups by correlation. Pairs of variables that showed the highest correlations for the absolute power results (bold numbers in table 5) were also correlated for the absolute work results. The internal work to speed correlation was 0.263; the correlation for the internal work/mass to speed was 0.287. The relationship between speed squared and work was 0.262 and between speed squared and work/mass was 0.287.

One sample graph from each subject is presented here. The graphs are presented to show that normal running was achieved. Note that none of the graphs presented in this section are from outlier or large leverage trials. The complete set of graphs for each subject can be found in appendix B. Major patterns of activity from the graphs are noted below. The graphs have not been rectified (i.e. made all positive to correspond to the new power equation) because it would then be impossible to distinguish concentric and eccentric work.

Ipsilateral Side - Power Curves

IFS — ITO. The dominant patterns seen in the ankle and knee curves in this section of the graphs are large dips in the curves caused by eccentric work followed by large peaks caused by concentric work. The maximum eccentric work, at the ankle, occurred at 25% of IFS— ITO. Generation of power started to occur around 50%. The ankle pattern was fairly consistent throughout all subjects, however, the peak concentric work was usually 25—75% greater than the peak eccentric work. The knee patterns do vary slightly from subject to subject. The peak eccentric work, in the knee, varied anywhere from 35 to 50% of IFS — ITO. Within subjects the eccentric and concentric work were consistent, however, between subjects these characteristics were drastically different. The hip powers were totally different than those of the ankle and knee. Generally, shortly after IFS was achieved, concentric work peaked followed by a burst of eccentric work. The eccentric work peaks were variable

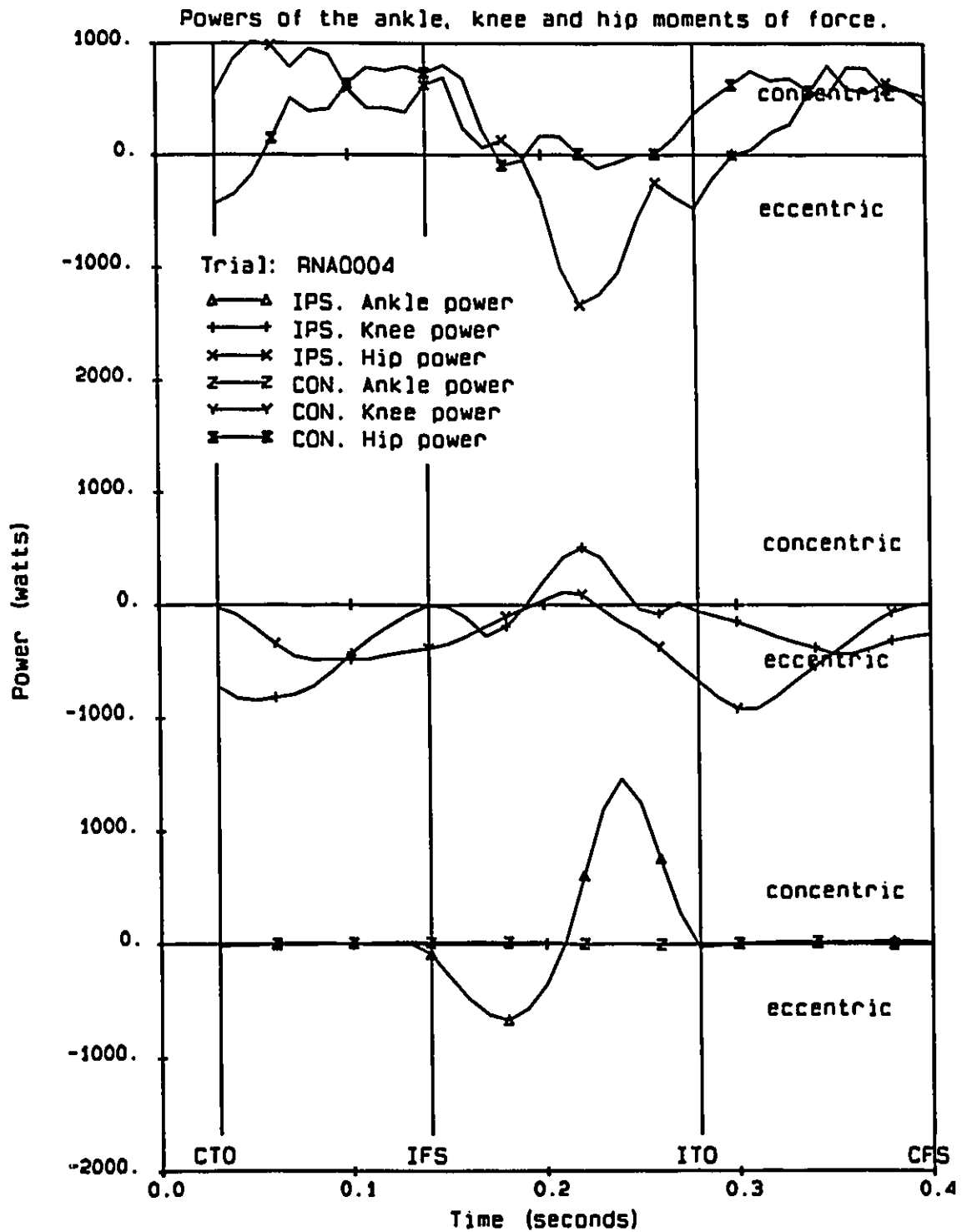


Figure 2: Sample power curve of the hip, knee and ankle joints for subject RNAO. IPS=ipsilateral and CON=contralateral side of the body. CTO=con. toe-off, IFS=ipso. foot strike, ITO=ipso. toe-off and CFS=con. foot strike.

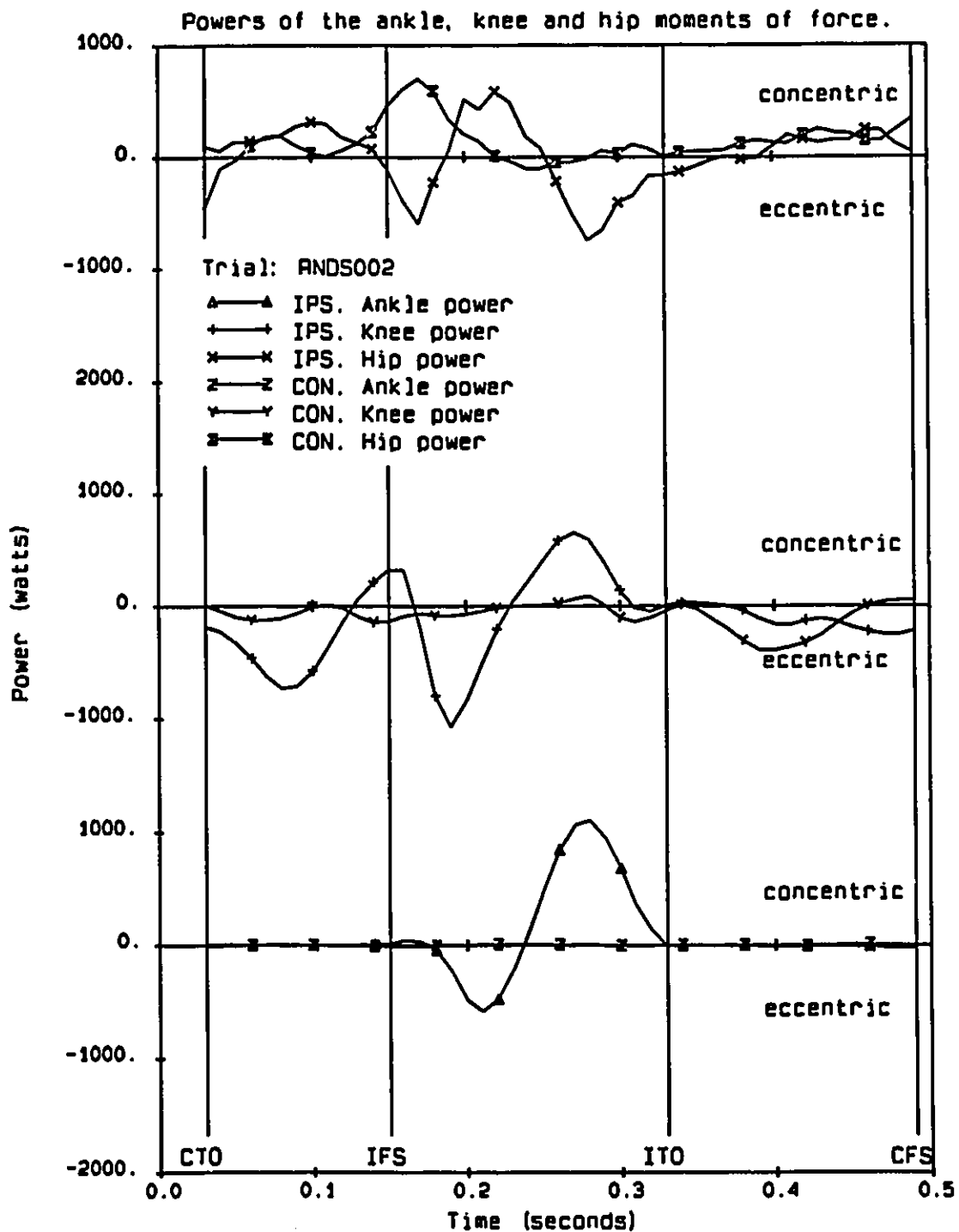


Figure 3: Sample power curve of the hip, knee and ankle joints for subject RNDS. IPS=ipsilateral and CON=contralateral side of the body. CTO=con. toe-off, IFS=ipso. foot strike, ITO=ipso. toe-off and CFS=con. foot strike.

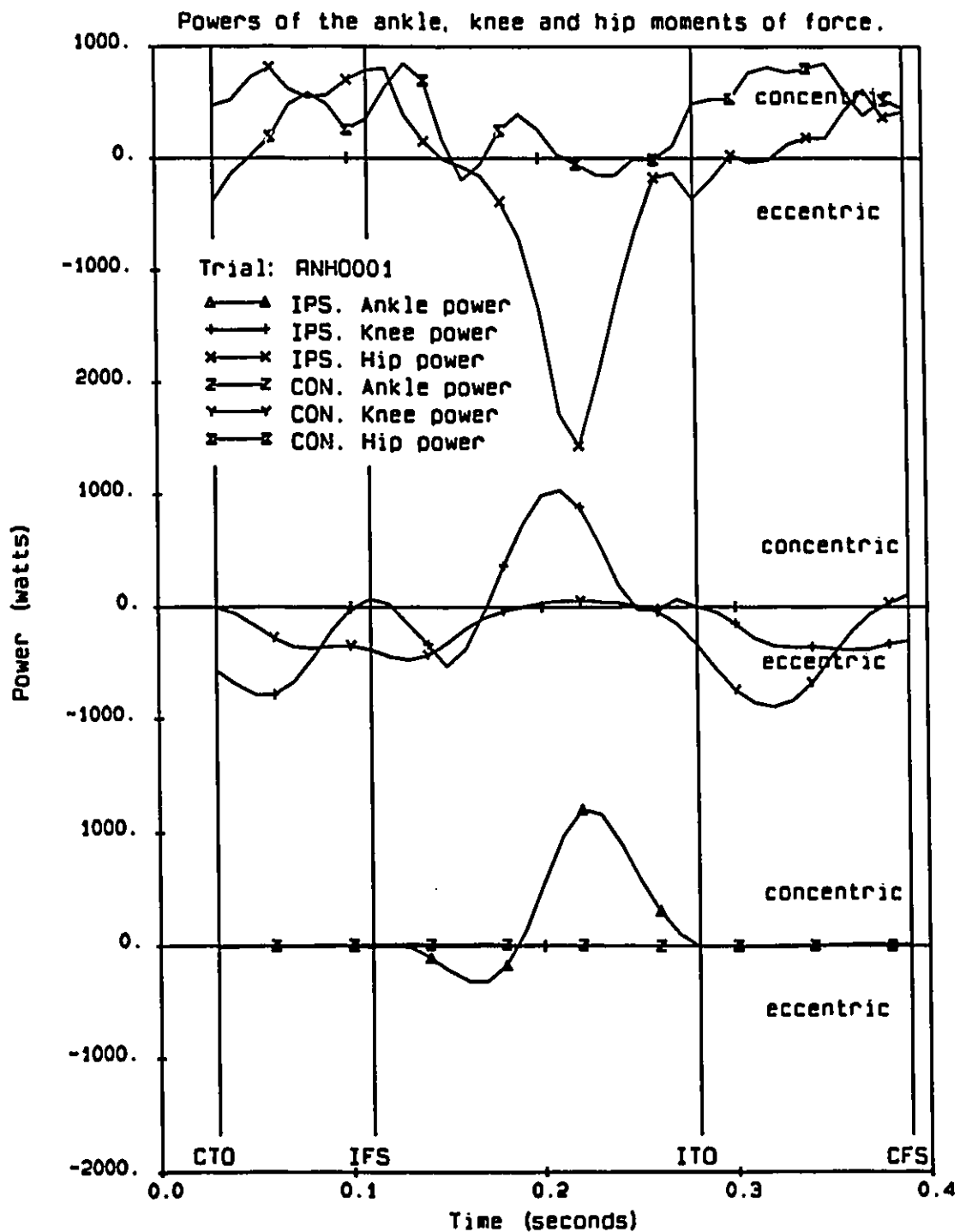


Figure 4: Sample power curve of the hip, knee and ankle joints for subject RNHO. IPS=ipsilateral and CON=contralateral side of the body. CTO=con. toe-off, IFS=ipso. foot strike, ITO=ipso. toe-off and CFS=con. foot strike.

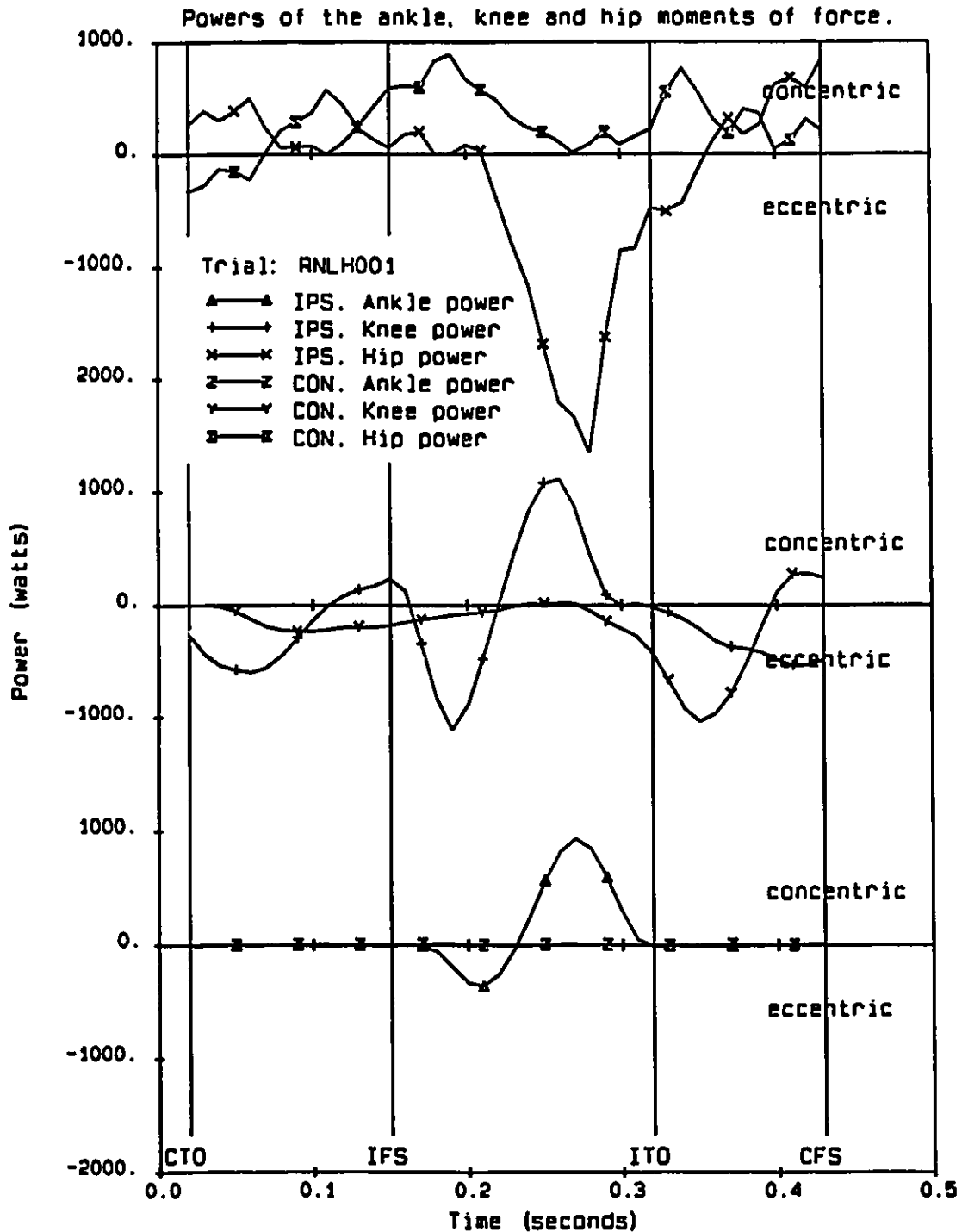


Figure 5: Sample power curve of the hip, knee and ankle joints for subject RNLH. IPS=ipsilateral and CON=contralateral side of the body. CTO=con. toe-off, IFS=ipso. foot strike, ITO=ipso. toe-off and CFS=con. foot strike.

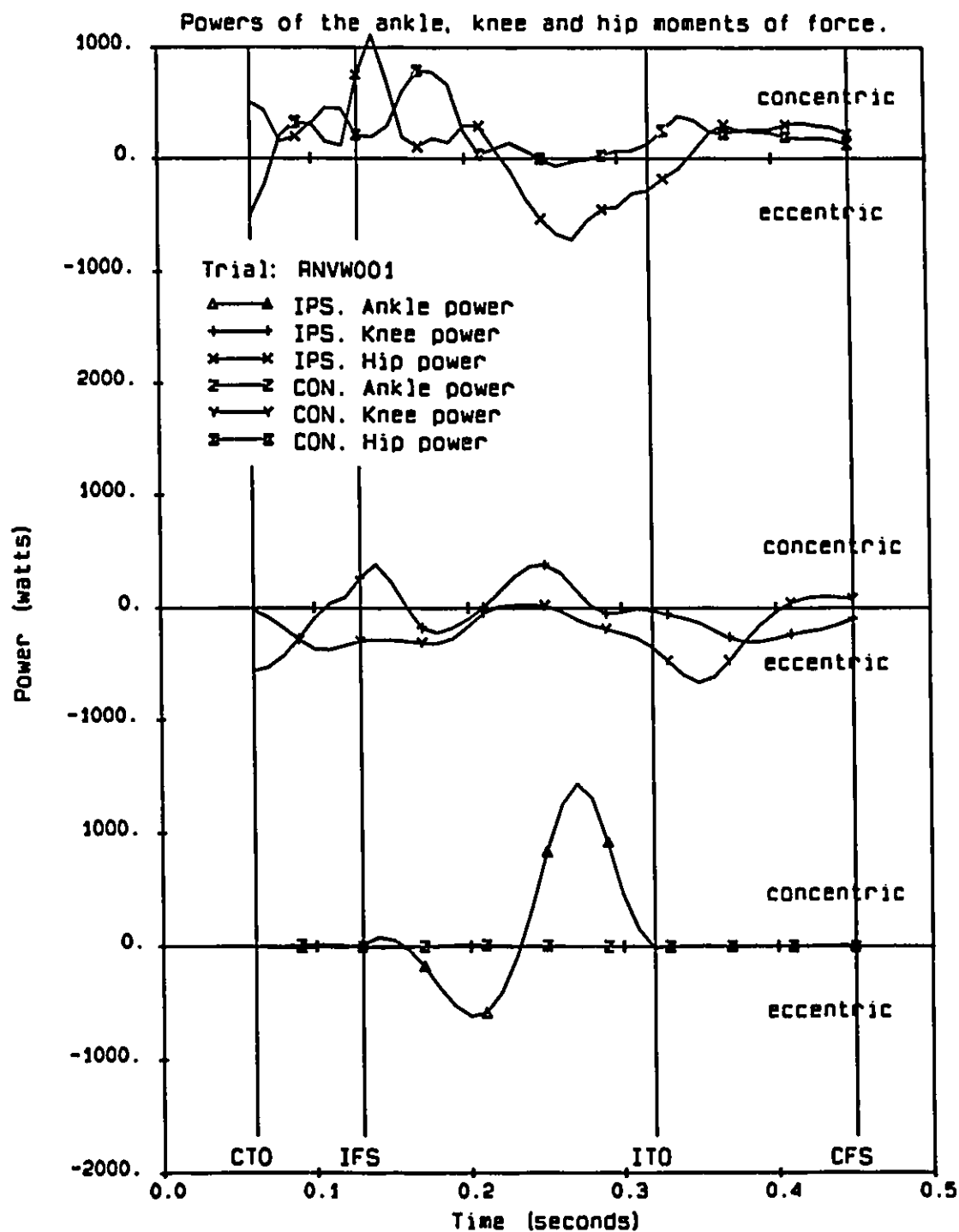


Figure 6: Sample power curve of the hip, knee and ankle joints for subject RNW. IPS=ipsilateral and CON=contralateral side of the body. CTO=con. toe-off, IFS=ipso. foot strike, ITO=ipso. toe-off and CFS=con. foot strike.

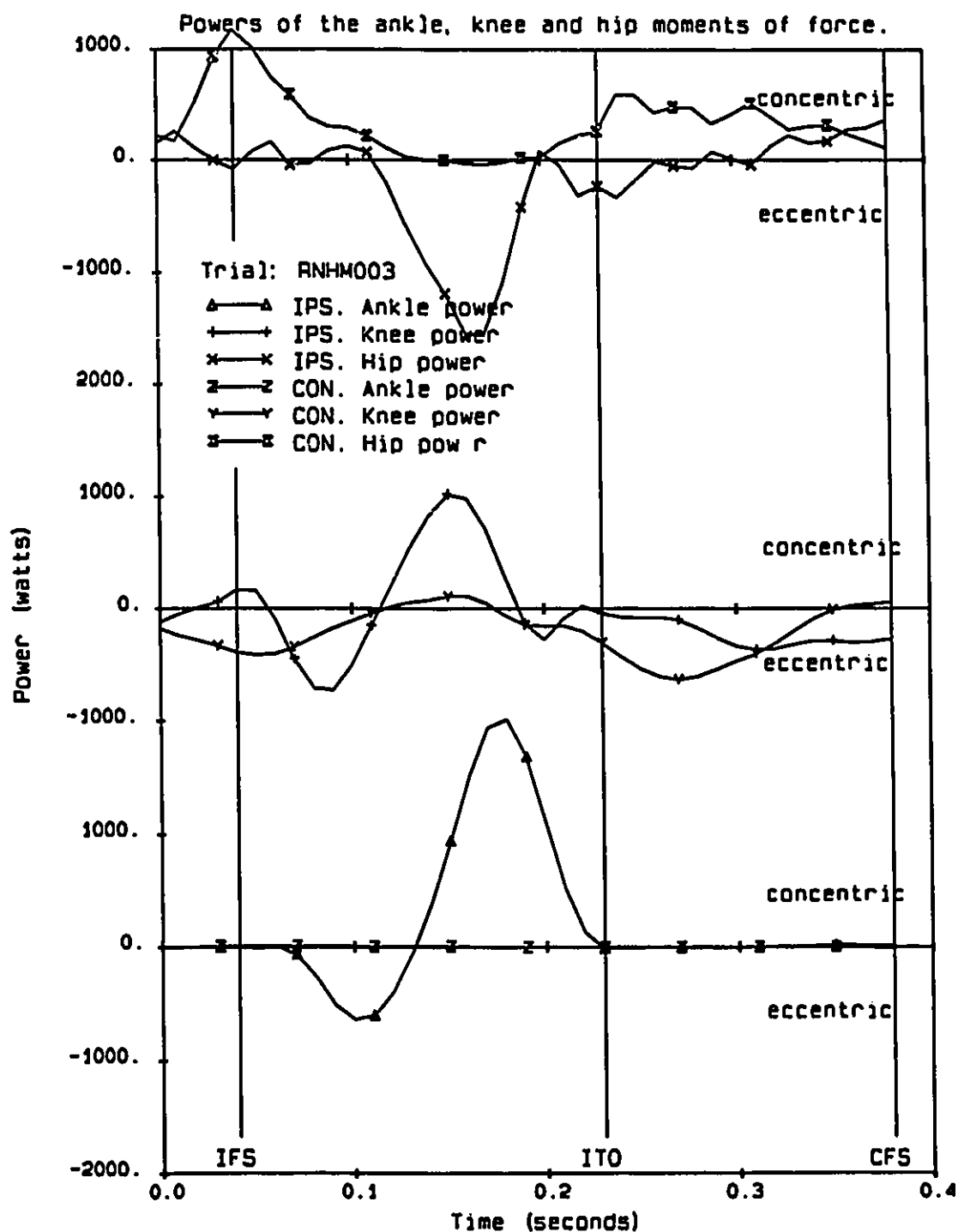


Figure 8: Sample power curve of the hip, knee and ankle joints for subject RNHM. IPS=ipsilateral and CON=contralateral side of the body. CTO=con. toe-off, IFS=ipso. foot strike, ITO=ipso. toe-off and CFS=con. foot strike.

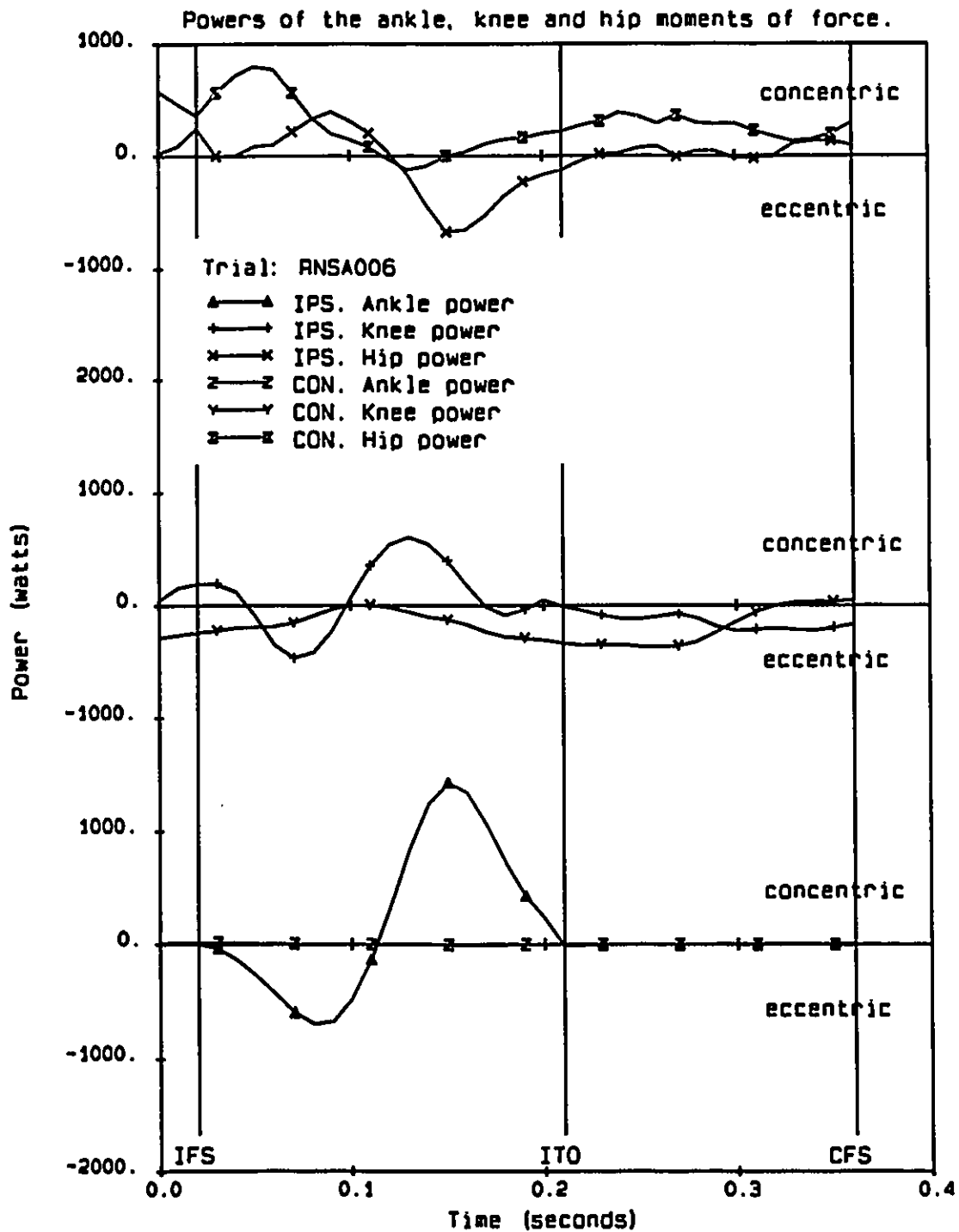


Figure 9: Sample power curve of the hip, knee and ankle joints for subject RNSA. IPS=ipsilateral and CON=contralateral side of the body. CTO=con. toe-off, IFS=ipso. foot strike, ITO=ipso. toe-off and CFS=con. foot strike.

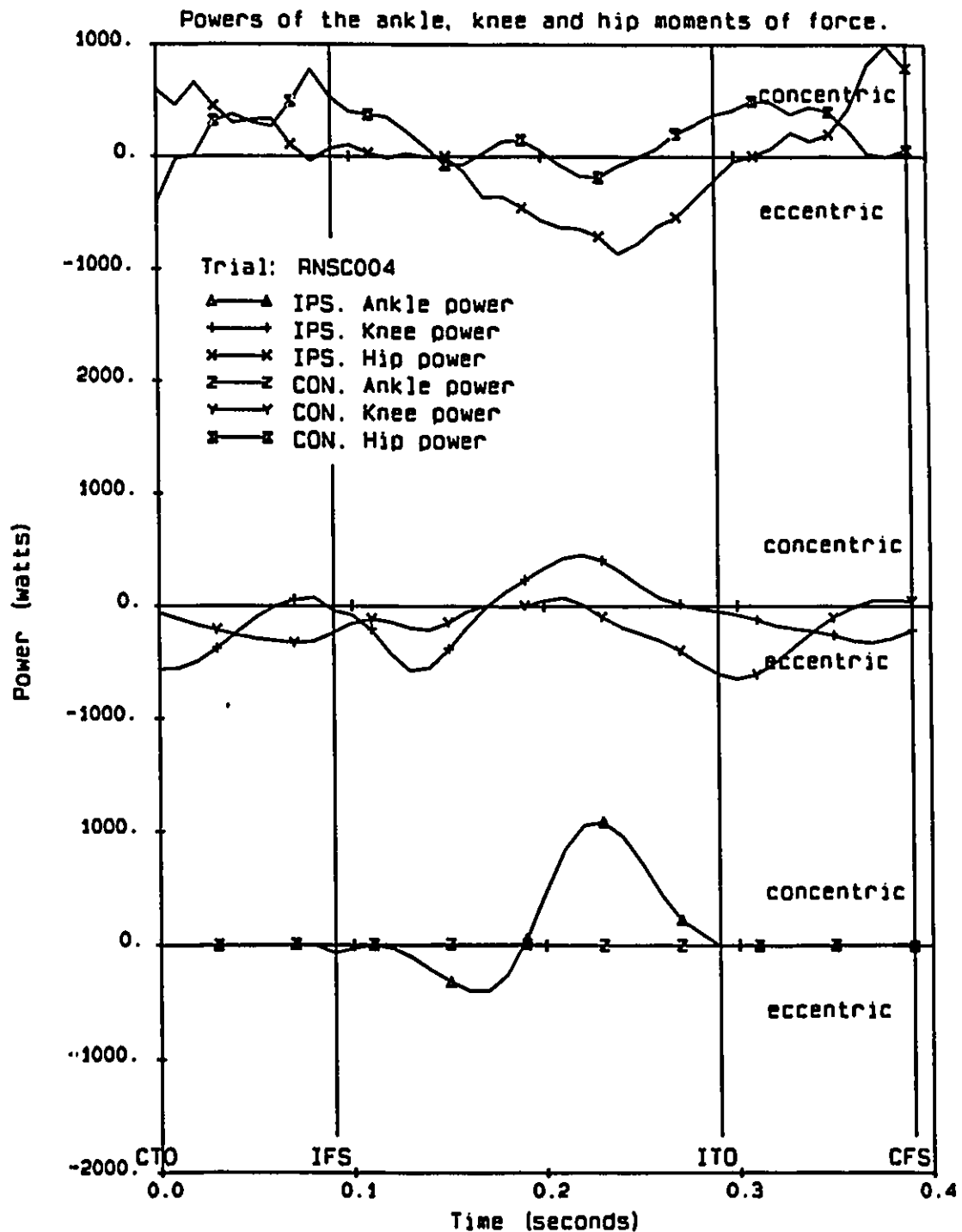


Figure 10: Sample power curve of the hip, knee and ankle joints for subject RNSC. IPS=ipsilateral and CON=contralateral side of the body. CTO=con. toe-off, IFS=ipso. foot strike, ITO=ipso. toe-off and CFS=con. foot strike.

between subjects but generally occurred after the midpoint of IFS — ITO, usually around the peak of the ankle and knee concentric work activity. Concentric work, at the hip, does not begin again until after ITO.

ITO — CFS. During swing, the ankle showed no power. The knee, in both trained and untrained runners, almost always showed increasing eccentric work until just before CFS. In the knee, ITO is the transition point of concentric to eccentric work. During this stage of running, the hip acts oppositely to the knee. While the knee is absorbing power, the hip is generating it.

Contralateral Side - Power Curves

IFS — ITO. The ankle powers of the contralateral side show little or no power throughout the motion. At the knee, virtually all trials showed eccentric work initially, slowly decreasing to eventually hits zero at 30—50% of this part of the step. Very few trials showed a generation of power at this point. The dominant pattern showed the curve dipping again. The only discernable pattern that could be identified in the contralateral hip curves in this section of the graph was the large sharp peak of concentric work that occurred at or just after IFS.

ITO — CFS. The peak of the very obvious eccentric work valley, in the knee, occurred generally just after ITO. The eccentric work decreased again and hit zero just before CFS. At the hip, another large concentric work peak occurred in this section of the graph. The peak occurred midpoint between ITO and CFS.

Discussion

The most interesting result of this study was the difference in IBC between the methods of calculation. It was always assumed that the absolute work method would give the lowest possible value for internal work of a cyclic movement (Aleshinsky, 1987). This assumption was based on the concept that positive work would be cancelled by negative work whenever synchronous movements occurred in opposite directions (Wells, 1988). This study has shown that the absolute work method gives, on average, three times the internal work value of the absolute power method. There are three reasons why this may have occurred in the present study.

The first reason has to do with conservation of energy by transferring energy within a segment. Once a limb has been pulled into rotation by muscles, it is possible that the muscles relax or perform very little activity to maintain the movement they created. The segment will usually swing into its final position conservatively. This occurs in the arms and legs in walking. The body also takes advantage of the use of gravity to reduce energy cost. At the end point of motion in the arm swing, after the arms have swung into position, they will swing back due to gravity. This effect, however, will be smaller because running is a faster motion. Again, the absolute work method will not realize this savings in its equations. The absolute

work method perceives all of the motion during running as generated kinetic energy, when in fact some of it is due solely to transfer of energy within the segment.

The second reason for the large differences in the two IBC values is also due to conservation of energy but by transfers between segments. Between segment transfers occur when one segment is actively rotated and the adjacent segment gets pulled along for the ride. Little muscle activation occurs in the adjacent segment, however, the absolute work method will detect work being done and thus overestimate IBC. This occurs often in the leg during swing phase. At the end of the kicking phase, the hip flexors pull the thigh through swing and the leg is whipped through swing as well. The absolute power method recognizes that no work has been performed in the adjacent segment because there is no power generation from muscles surrounding the joints of that segment.

The third reason the two results may be vastly different is because the principle that absolute work is based on is flawed. In a paper by Williams and Cavanagh (1983) the authors explored five different methods for calculating mechanical work. Four of the papers they examined dealt with pseudowork. Even though the present study's absolute work equations are one generation past the pseudowork equations, both are based on the same numbers—only the absolute value bars are placed differently (see absolute work equations in methodology section).

$$Pseudowork = \left(\sum_{k=1}^N \sum_{j=1}^S |\Delta PE_{i,k}| + |\Delta KE_{i,k}| + |\Delta RE_{i,k}| \right)$$

(Norman et al., 1976)

Williams and Cavanagh's (1983) paper noted large discrepancies in power values between four studies even though all the papers ran their subjects at similar speeds and used the absolute work method to calculate the values. Williams and Cavanagh stated that they did not know the reasons for the discrepancies. Two of the papers, Norman et al. (1976) and Gregor and Kirkendall (1978), ran their subjects at 3.6 m/s. The mean mechanical powers were 172 W and 163 W, respectively. The other papers were both by Luhtanen and Komi (1978, 1980). They ran their subjects at 3.9 m/s, however, their mean mechanical power results were 931 W and 1650 W, respectively. The first two studies were of treadmill running; which must account for the difference in values from the second set. This does not, however, explain the 719 W difference between the two Luhtanen and Komi studies. This difference is difficult to explain except to say that either the equations were flawed or the collection of the data in the latter studies was flawed.

Not only does the literature support the absolute power model but the stability of the IBC values also supports the absolute power model. In all cases, except for one subject (RNLH) the coefficient of variation was lower for the absolute power results compared to the absolute work results (tables 1 to 4). The coefficient of variation is a variability-to-signal ratio expressed as a percentage. Thus, the intra-subject variability is lower in the IBCs from the absolute power method.

Another statistic that supports the absolute power method is correlation. It was clear from the results that the correlations for work/mass to speed from the absolute power method were much higher than those from the absolute work method. One expects that increased speed requires increased mechanical work. Therefore work/mass to speed should be correlated. It is

important to realize, however, that the speeds that were tested represent only a small range of possible speeds. Caution must be taken when extrapolating the results beyond the range tested in this study. For example, sprinting and walking may not have the same goal as running, thus, any inferences made from this study to those movements should be viewed with a discriminating eye.

The absolute power model has been shown to be a more stable measure. It has not been shown to be more valid. Astrand and Rodahl (1986) stated that the energy cost of running within a wide range of speeds per kilometre is practically the same. That cost is around 4 ($\text{kJkg}^{-1}\text{km}^{-1}$). This means that the average physiological running cost is 4 ($\text{Jkg}^{-1}\text{m}^{-1}$). If an average stride length was 2 metres, then the average cost for trained runners, according to the absolute work method, is 13.52 ($\text{Jkg}^{-1}\text{m}^{-1}$) and the average cost according to the absolute power method is 4.375 ($\text{Jkg}^{-1}\text{m}^{-1}$). The cost for untrained runners is 11.315 ($\text{Jkg}^{-1}\text{m}^{-1}$) and 4.25 ($\text{Jkg}^{-1}\text{m}^{-1}$) for the absolute work method and absolute power method, respectively. The absolute work values are much higher than the estimated physiological cost. The absolute power values still overestimate the cost, however, the values are more realistic when comparing them to the absolute work approach. The absolute power method over estimates the work because it still does not account for storage and reuse of elastic energy.

It has been shown in the previous section that the absolute work model will overestimate the internal work of level running. The absolute work model will also fail in other situations. Aleshinsky (1986) cited an example of a cyclist working with no load and then tested again working with an applied load. If the cyclist was moving on level ground at the same speed in both tests, the absolute work method would calculate the same internal work

done. The absolute power method would give a higher value for the loaded task because it would examine one of the basic elements involved in activity, the generation of power by the muscle. Obviously the two works from the two cycling trials are not the same and the absolute power method in this situation detects a difference. The question that must be asked then is, if the absolute power method can detect a difference between two types of cycling, why did it fail to detect a difference between the two groups of runners?

The Absolute Power Model

One plausible reason that the absolute power method did not detect a difference is that there was no difference. This relates back to whether or not running is a highly skilled movement. It appears that running at submaximal and unfatigued is not very different for trained and untrained runners. Another task that is more novel or that has never been performed by the untrained subjects probably would have yielded significant differences.

If running does take skill, there are many variables in a laboratory setting that may be inhibiting this skill. The subjects had a very short runway. It is likely, the runners were concentrating on getting up to speed prior to data collection and then immediately following data collection, they had to concentrate on slowing down so not to hit the padding at the end of the runway too hard. This surely inhibited technique of the trained runners. It would have been better, if possible, to collect data in the middle of a race once the runner had a chance to "get into her groove".

Another obstacle still to overcome is the magnitude of the error associated with linked-segment analysis. If the error was reduced, a significant difference between the two groups

may have been found. The problem with this variable does not lie in the equations but the data reduction methods and the assumption of rigid bodies. This problem can be reduced if more trials were performed by each subject. Unfortunately, the cost of film and the time required to manually digitize each trial precluded this option.

Lastly, it is possible that there was a difference between the groups but due to the inability to account for factors such as stored elastic energy, the model did not detect this difference. Robertson and Winter (1980) hinted that faster speeds of walking are not obtained by just increasing plantar flexor activity but by some sort of more complex strategy. Perhaps the strategy involves use of stored elastic energy. The absolute power model does not account for any savings in energy usage via stored elastic energy. A highly skilled individual may make more efficient use of the stored energy than a non-skilled individual. The model, however, will identify reuse of elastic energy as new energy being generated and the storage of elastic energy as being eccentric work.

Power Curves

The ipsilateral and contralateral sides of the body have consistent patterns that can be seen within the power curves at the different joints. The most consistent patterns noted were in the ipsilateral ankle and knee power curves. These patterns are consistent with normal running patterns.

The large absorptions (called A1 at the ankle and K1 at the knee) seen after IFS were caused by the ankle dorsiflexing and knee flexing to absorb the impact. The ankle plantarflexors and the knee extensors were acting eccentrically so the leg did not collapse.

Following the large absorption, there was an even larger generation of power. This will be called A2 in the ankle and K2 in the knee. These concentric works occurred to propel the runner and start the running cycle. A2 was caused by the ankle extensors, gastrocnemius and soleus, activating to initiate and follow through with push off. K2 was a direct result of quadriceps concentric activity.

Throughout the time that A1, A2 and K1, K2 were occurring, the ipsilateral hip was acting oppositely to the ankle and the knee. During initial concentric activity at the ankle and knee, the extensors extended the hip to preparation for IFS. As soon as IFS occurred, the concentric work decreased and became negative. At this stage, the hip extensors, such as the glutei, were attempting to stop the flexing of the hip during impact. The momentum of the trunk moving forward was so great, that the extensors had to work past ITO to control this motion. If the extensors did not provide this service, the trunk would simply fall forward and then collapse onto the lower body. After toe-off, the ankle moments produced no work and no power is indicated on the graphs. The knee extensor moment, however, did show eccentric work. This absorption was caused by the quadriceps slowing the flexing of the knee down near the end of the flexing phase. The flexors at the hip were now activated producing positive work. The final concentric work that is seen before CFS were these flexors pulling the leg through the motion during the first half of the swing phase.

The contralateral side of the body also exhibited certain patterns. The contralateral side of the body is in swing phase. The ankle power curve, of course, indicated no power generations or absorptions. The knee initially showed that some of the muscles across the joint were working eccentrically. The contralateral leg just finished the kick phase of running. The

quadriceps primary job at this stage was to prevent the subject from kicking herself in the buttock, thus the eccentric activity pattern. Very little power at the knee was seen between the large bursts of eccentric activity. The leg was whipped through the swing motion due to the large generation of power that the hip flexors created just after IFS. The hip pulled the thigh through the motion. This is one area where all the subjects conserved energy. As previously mentioned, the absolute work method did not distinguish this savings.

In the middle of the swing phase, eccentric muscle activity was present, in the muscles that crossed the knee, in the majority of the subjects. The knee flexors slowed and eventually stopped the knee from extending. This type of activity is often referred to as a safety mechanism. It prevents our joints from overextending, which has a potential to occur in maximal activities such as sprinting, and creating injury. It was also used in this submaximal activity to a lesser extent. During this time, the hip musculature was generating a large amount of power. The hip extensors were attempting to extend the hip in preparation for CFS.

Conclusions

While there is a wealth of information presented here, some definite conclusions can be made. The power curves demonstrate that similar strategies for running were used by all subjects during individual trial data collection. This shows that normal running was achieved. With this in mind, it can be said that the absolute power model is a more stable measure of IBC of running and it gives a more reliable estimate of IBC of running in a laboratory setting. This conclusion is corroborated by more stable coefficients of variation and higher correlations between work, mass and speed for the absolute power model compared to the absolute work

model and closer resultant values of IBC for the absolute power model when compared to the cost of running as stated in Astrand and Rodahl (1986). The results also indicated that there is no difference between trained and untrained runners, in a laboratory setting, performing unfatigued running.

It is clear that the absolute work approach does not treat transfers of energy, between and within segments, correctly (Caldwell and Forrester, 1992). Unfortunately, not every researcher has a force platform at his/her disposal, nor is it always convenient to use a force platform in certain types of situations—so the absolute power approach cannot be used. Perhaps one future focus for this type of research is to examine exactly how the absolute work method defines transfers of energy and try to correct the problem. As for the absolute power approach, to achieve significant results, one direction is to look into highly skilled or unfamiliar movements. Running is not highly skilled and is not a novel enough task to determine differences between elite and untrained athletes. The modelling process must also be improved to achieve significant results. Variables such as stored elastic energy should be included or estimated more accurately and the error in data collection and analysis must be reduced to improve the model's sensitivity. Increasing the number of subject trials will allow for ensemble averaging of data and it will help reduce the variability.

Glossary of Terms

Absolute Power (internal work)—Sum of the absolute value of the powers produced at each joint summed across the number of samples in a cycle minus the external work performed over all the samples in the cycle.

Absolute Work (internal work)—Sum of the absolute values of the total change in mechanical energies of the segments over time minus the external work performed during that time period.

Energy Approach—Uses segmental mechanical energies calculated from kinematic data and anthropometrics to calculate work.

External Work—Work done by the body on an external load or the body's mass.

Internal Work—Work required to move the body segments through a cyclic movement.

IBC—Internal work done divided by the mass of the body and by the speed of the movement (in this study running speed).

Mechanical Efficiency—Ratio of the mechanical work done over the physiological cost.

Power Approach—Uses external force data and inverse dynamics to calculate work. Sometimes referred to as joint-work in the literature.

Pseudowork—An approach to calculating work that does not include any energy transfers.

TPW—same as W_n .

W_n —Pseudowork calculation for internal work.

W_w —Calculation for internal work that assumes transfers of energy within but not between segments.

W_{wb} —Energy approach calculation for internal work that assumes both within and between segment energy transfers.

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Appendix A: Tabular Results for Individual Trials

Table 6: Absolute Work method results for trained runners.

Subject Trials	Mass (kg)	Speed (m/s)	Int. Work (J)	Int.Work/Mass (J/kg)	IBC (J/kg)/(m/s)	C.V. (%)
rnds002	52.0	5.63	1707.70	32.84	5.83	21.5
006		5.79	1631.67	31.38	5.42	
010		5.96	1561.80	30.03	5.04	
011		5.53	2292.53	44.09	7.97	
015		5.70	2518.60	48.43	8.50	
avg.		5.72	1942.46	37.35	6.55	
rnao004	59.1	6.90	1490.06	25.21	3.65	15.1
005		7.06	1169.32	19.79	2.80	
007		7.17	1787.58	30.25	4.22	
008		7.24	1349.52	22.83	3.15	
009		7.22	1283.10	21.71	3.01	
avg.		7.12	1415.92	23.96	3.37	
rnvw001	49.1	5.51	1023.59	20.85	3.78	2.77
002		5.88	873.43	17.79	3.03	
004		5.79	1111.23	22.63	3.91	
005		5.72	1733.68	35.31	6.17	
006		5.82	934.60	19.03	3.27	
avg.		5.74	1135.31	23.12	4.03	
rnli001	61.7	6.77	2045.73	33.16	4.90	10.3
002		6.28	1989.83	32.25	5.14	
003		6.14	1964.50	31.34	5.19	
004		6.31	2136.10	34.62	5.49	
007		6.54	1609.24	26.08	3.99	
avg.		6.41	1949.08	31.59	4.94	
rnho001	65.8	6.20	1528.73	23.23	3.75	24.8
004		6.17	1131.73	17.20	2.79	
007		6.55	794.79	12.08	1.84	
009		6.38	1079.48	16.41	2.57	
avg.		6.33	1133.68	17.23	2.74	
POP.AVG.	57.5	6.26	1531.19	27.04	4.39	21.9

Table 7: Absolute Work method results for untrained runners.

Subject	Mass (kg)	Speed (m/s)	Int. Work (J)	Int.Work/Mass (J/kg)	IBC (J/kg)/(m/s)	C.V. (%)
rnhm001	67.7	5.80	1415.92	20.94	3.61	15.2
003		5.64	1734.03	25.61	4.54	
004		5.30	2010.72	29.70	5.60	
005		5.19	1573.95	23.25	4.48	
007		5.84	1578.78	23.32	3.99	
avg.		5.55	1662.68	24.56	4.44	
rns004	55.5	5.23	1216.01	21.91	4.19	18.2
006		5.31	1374.83	24.77	4.67	
007		5.28	777.29	14.01	2.65	
008		4.89	1064.71	19.18	3.92	
009		5.57	1424.92	25.67	4.61	
avg.		5.26	1171.55	21.11	4.01	
rn1001	53.9	7.57	1797.05	33.34	4.40	25.6
002		6.77	909.43	16.87	2.49	
004		8.02	2116.28	39.36	4.90	
006		7.23	1170.79	21.72	3.00	
007		7.18	1915.81	35.54	4.95	
avg.		7.35	1581.87	29.35	3.95	
rnft002	51.8	4.93	729.23	14.08	2.86	31.3
003		4.63	611.52	11.81	2.55	
005		4.80	1284.54	24.80	5.17	
006		4.93	678.82	13.10	2.66	
008		4.82	1174.30	22.67	4.70	
avg.		4.82	895.68	17.29	3.59	
rnsa005	71.8	4.76	1583.40	22.05	4.63	24.5
006		5.22	1097.90	15.29	2.93	
008		5.31	2162.55	30.12	5.67	
009		5.14	1186.40	16.52	3.21	
010		5.36	1457.01	20.29	3.79	
avg.		5.16	1497.45	20.86	4.05	
POP. AVG.	60.1	5.63	1361.85	22.63	4.01	40.2

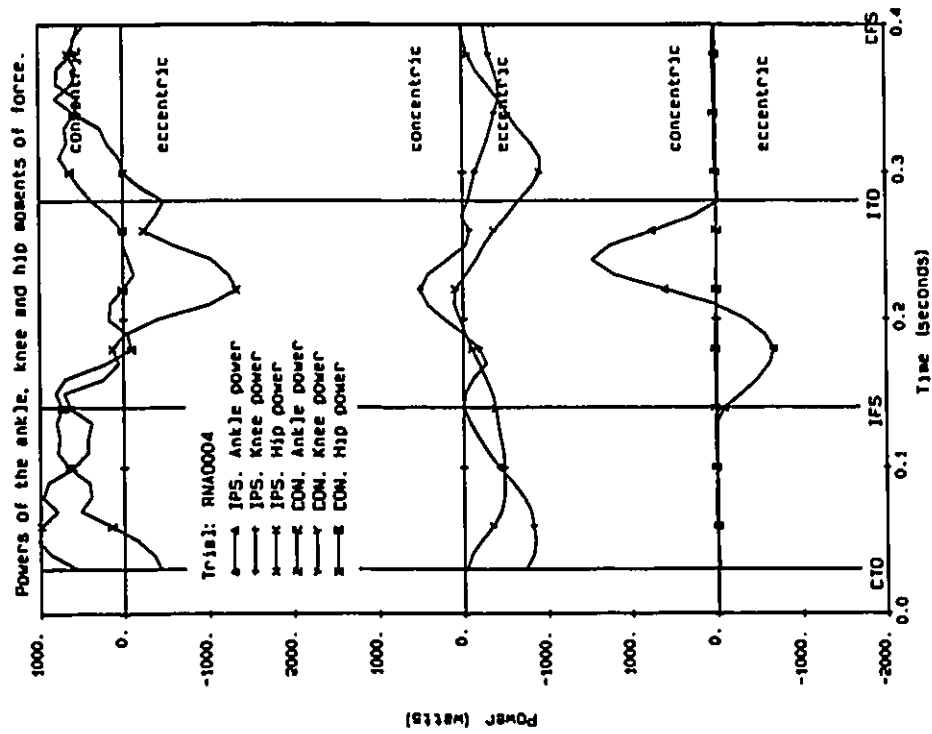
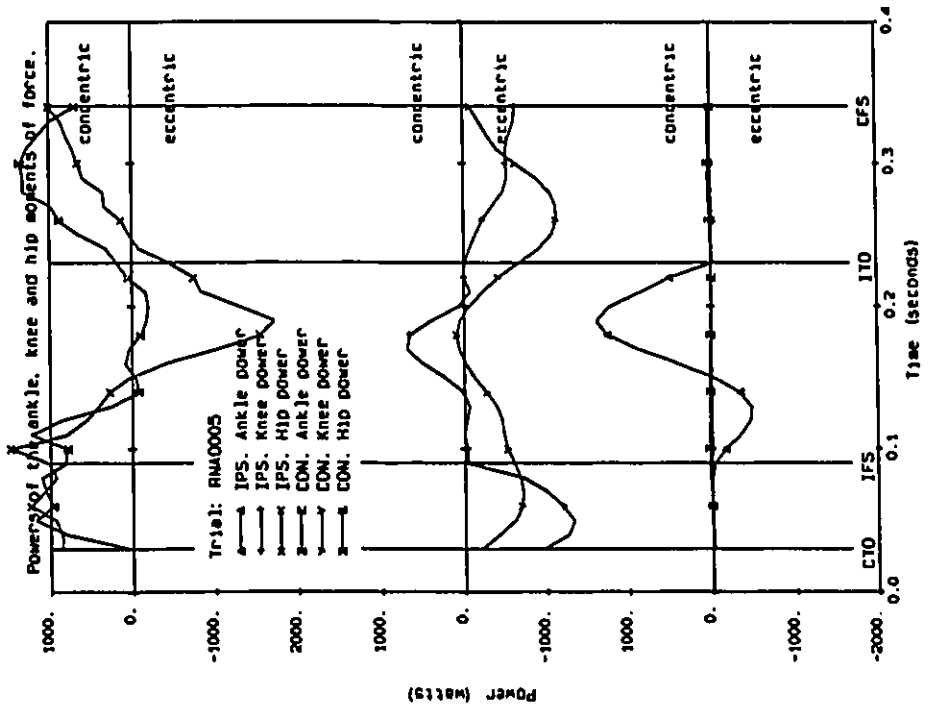
Table 8: Absolute Power method results for trained runners.

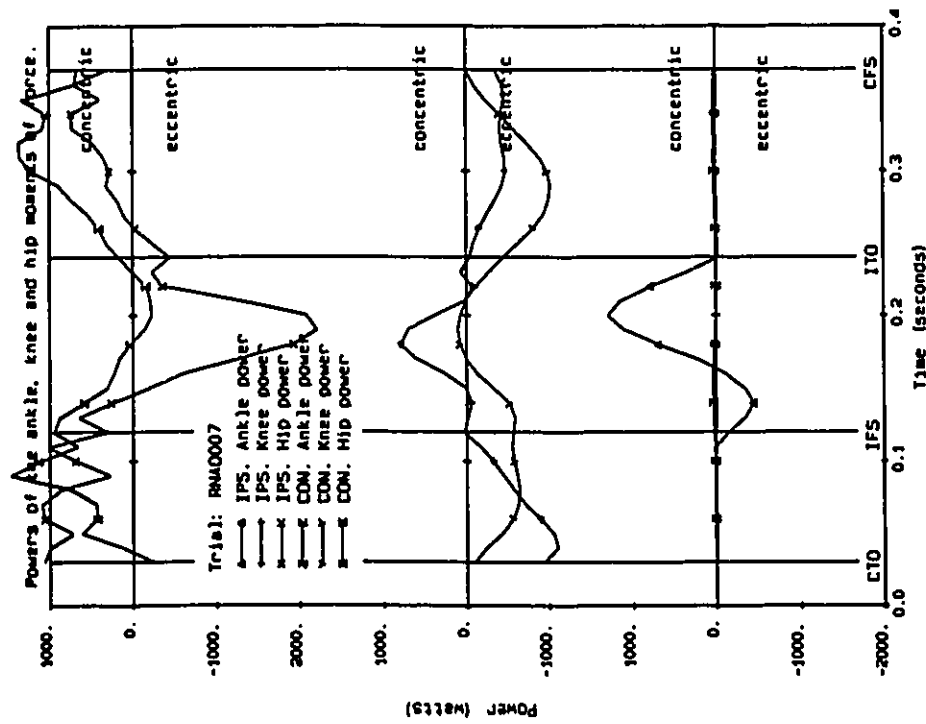
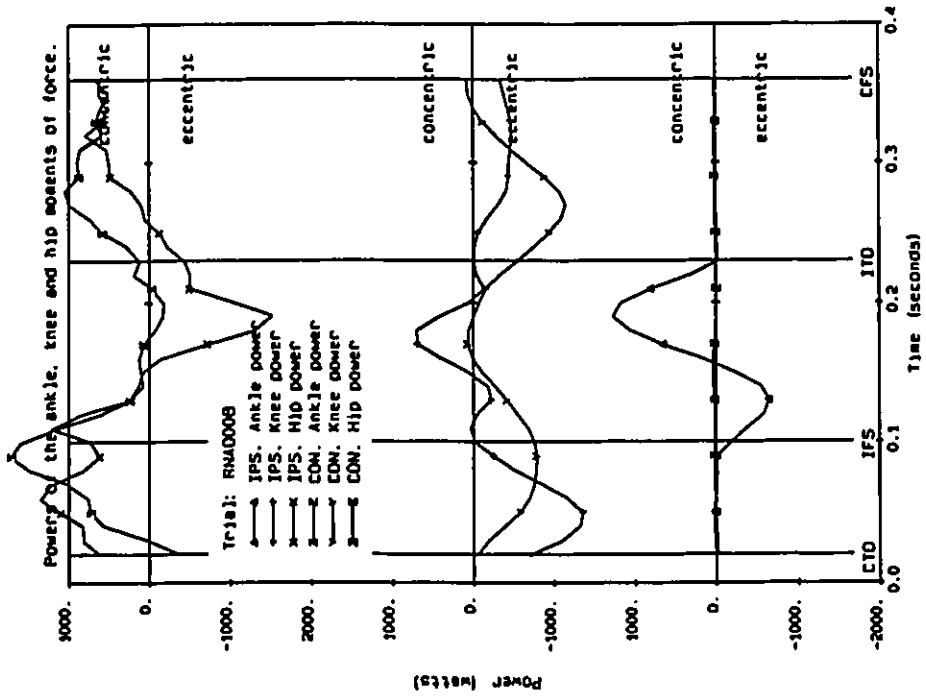
Subject	Mass (kg)	Speed (m/s)	Int. Work (J)	Int.Work/Mass (J/kg)	IBC (J/kg)/(m/s)	C.V. (%)
rnds002	52.0	5.63	359.7	6.92	1.23	7.8
006		5.79	367.7	7.07	1.22	
011		5.53	381.1	7.33	1.33	
015		5.70	315.6	6.07	1.06	
avg.		5.72	356.0	6.85	1.21	
rnao004	59.1	6.90	545.5	9.23	1.34	8.1
005		7.06	657.0	11.12	1.57	
007		7.17	659.3	11.16	1.56	
008		7.24	606.1	10.26	1.42	
009		7.22	546.6	9.25	1.28	
avg.		7.12	602.9	10.44	1.43	
rnvw001	49.1	5.51	383.4	7.81	1.42	4.6
002		5.88	413.9	8.43	1.43	
004		5.79	356.5	7.26	1.25	
005		5.72	382.0	7.78	1.36	
006		5.82	386.7	7.88	1.35	
avg.		5.74	384.5	7.83	1.36	
rnlh001		61.7	6.77	683.6	11.08	
002	6.28		845.4	13.70	2.18	
003	6.14		543.6	8.81	1.43	
004	6.31		571.8	9.27	1.47	
007	6.54		767.4	12.44	1.90	
avg.	6.41		638.8	11.05	1.72	
rnho001	65.8	6.20	570.0	8.66	1.40	14.2
004		6.17	405.7	6.17	1.00	
007		6.55	453.4	6.89	1.05	
009		6.38	439.3	6.68	1.05	
avg.		6.33	467.1	7.10	1.12	
POP. AVG.	57.5	6.26	506.1	8.75	1.39	19.0

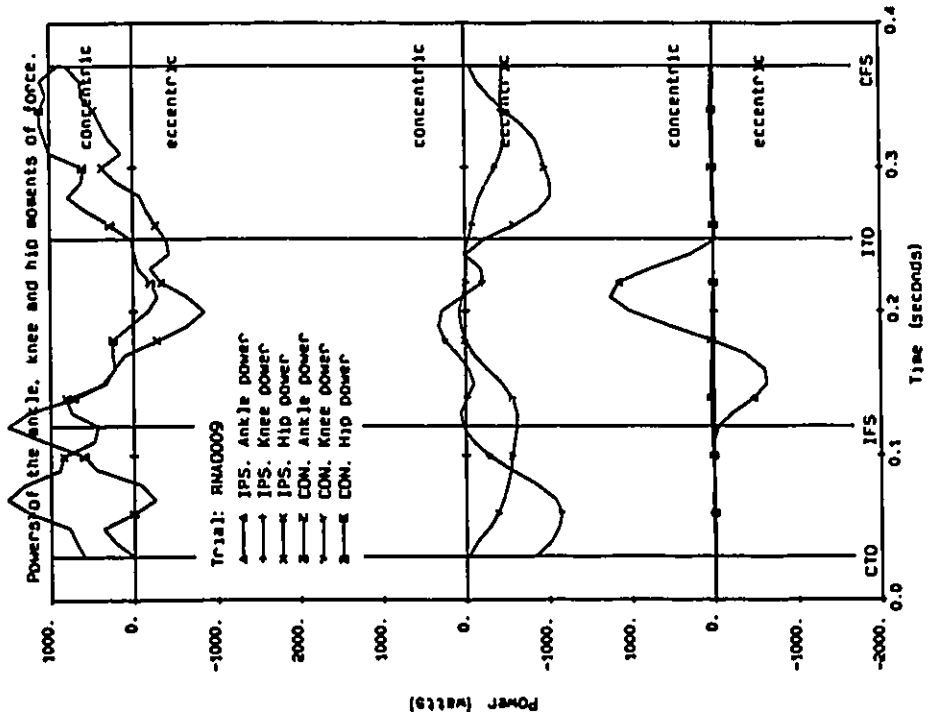
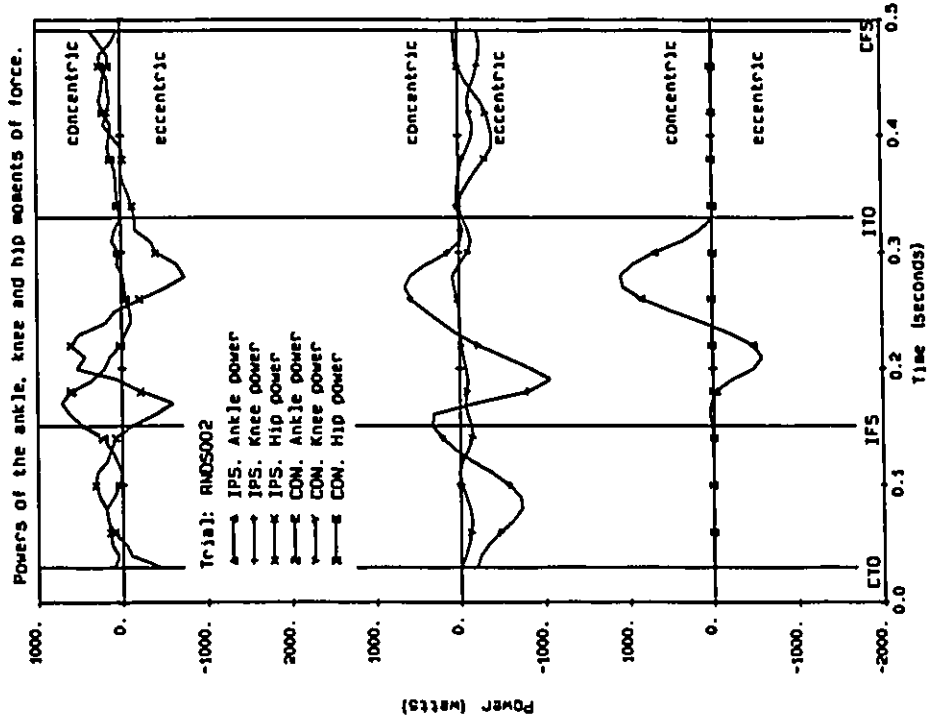
Table 9: Absolute power method results for untrained runners.

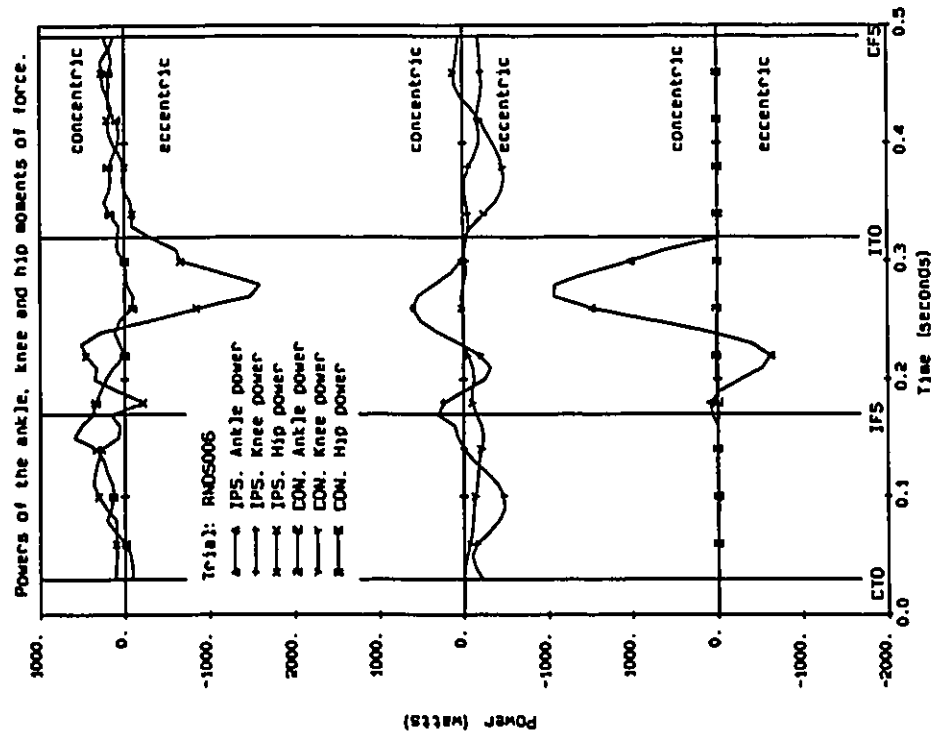
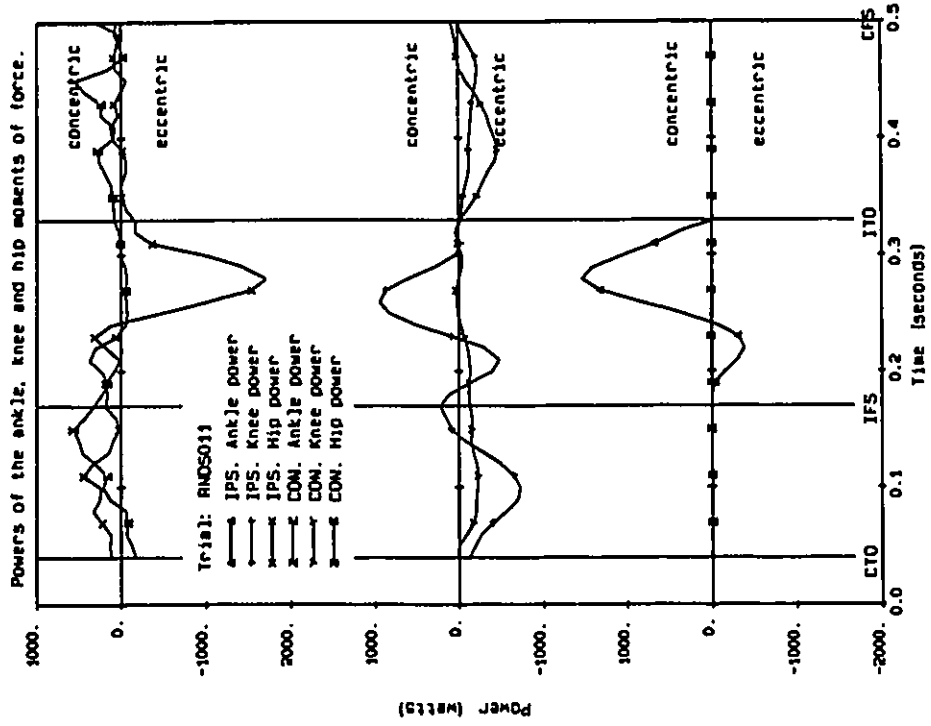
Subject	Mass (kg)	Speed (m/s)	Int. Work (J)	Int. Work/Mass (J/kg)	IBC (J/kg)/(m/s)	C.V. (%)
rnhm001	67.7	5.80	712.5	10.52	1.81	13.8
003		5.64	564.1	8.33	1.48	
004		5.30	670.0	9.90	1.87	
005		5.19	571.8	8.45	1.63	
007		5.84	499.0	7.37	1.26	
avg.		5.55	603.5	8.51	1.61	
rmsc004	55.5	5.23	455.4	8.21	1.57	7.6
006		5.31	371.2	6.69	1.26	
007		5.28	391.4	7.05	1.34	
008		4.89	392.4	7.07	1.45	
009		5.57	456.2	8.22	1.48	
avg.		5.26	413.3	7.26	1.42	
rmyl001	53.9	7.57	628.3	11.66	1.54	6.9
002		6.77	596.3	11.06	1.63	
004		8.02	740.2	13.73	1.71	
006		7.23	572.6	10.62	1.47	
007		7.18	689.5	12.79	1.78	
avg.		7.35	645.4	12.05	1.63	
rmt003	51.8	4.63	346.8	6.69	1.45	4.5
006		4.93	337.9	6.52	1.32	
008		4.82	365.8	7.06	1.47	
avg.		4.82	350.2	6.76	1.41	
rmsa006	71.8	5.22	416.2	5.80	1.14	9.8
008		5.31	404.3	5.63	1.06	
009		5.14	447.2	6.23	1.21	
010		5.36	525.7	7.32	1.37	
avg.		5.16	448.4	6.24	1.19	
POP.AVG.	60.1	5.63	507.0	8.50	1.47	14.9

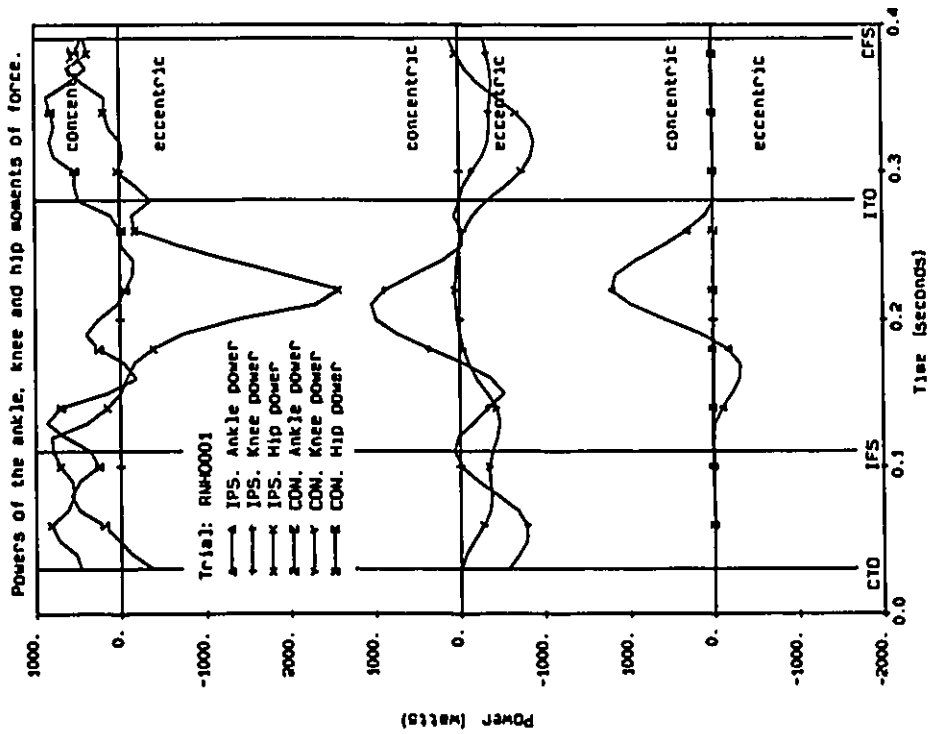
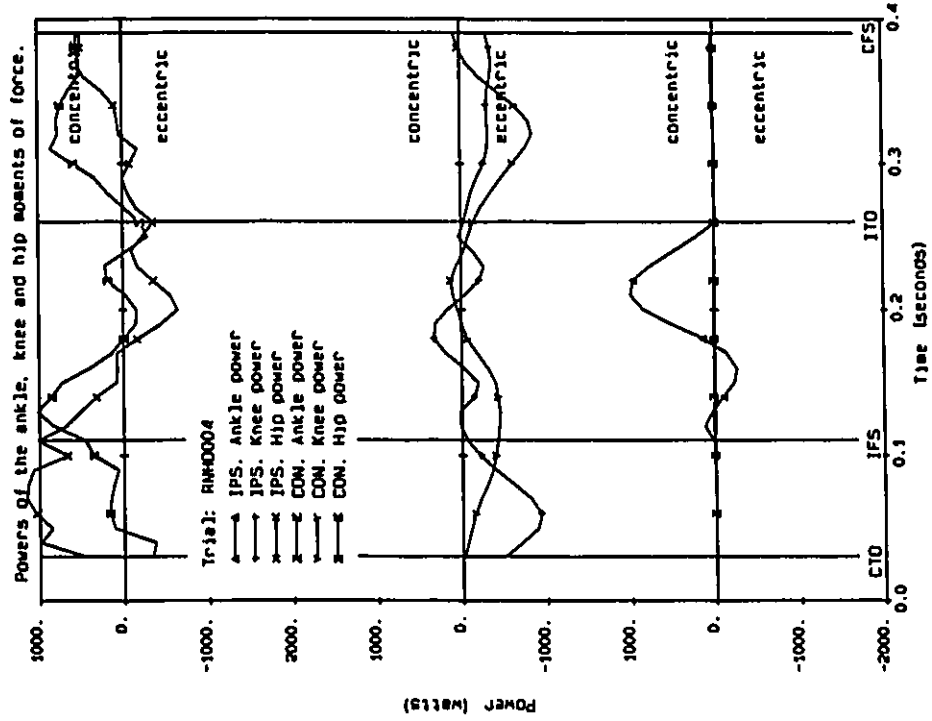
Appendix B: Power Curves for Individual Trials

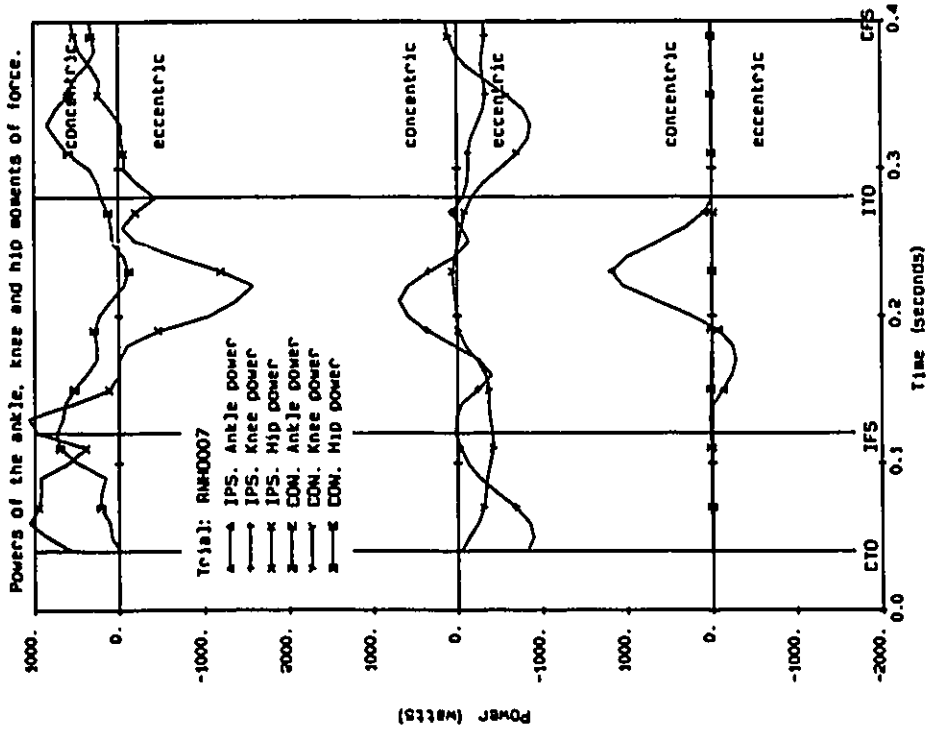
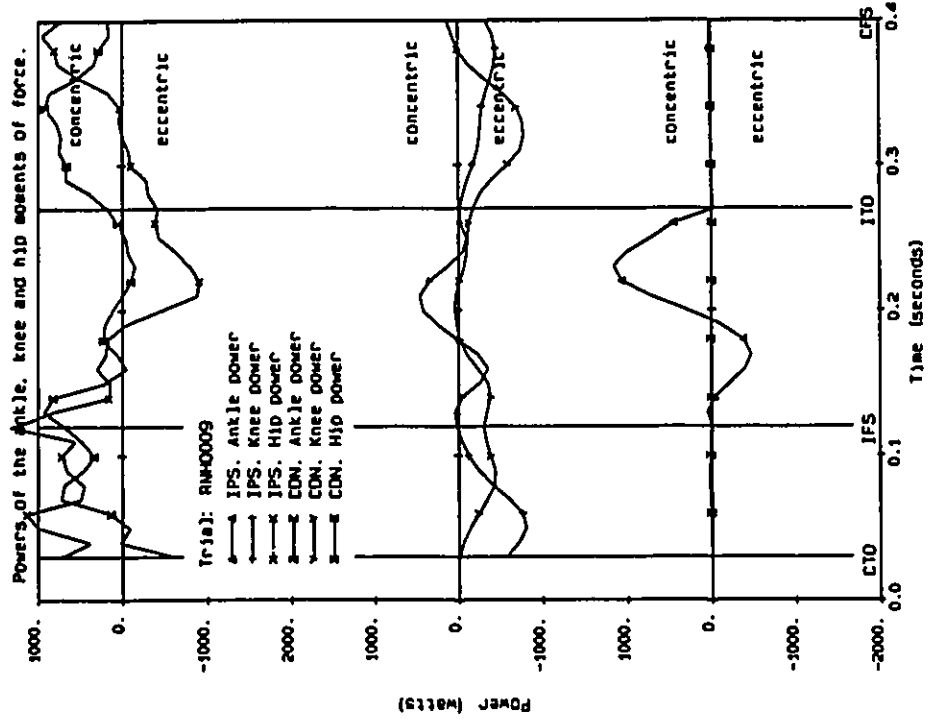


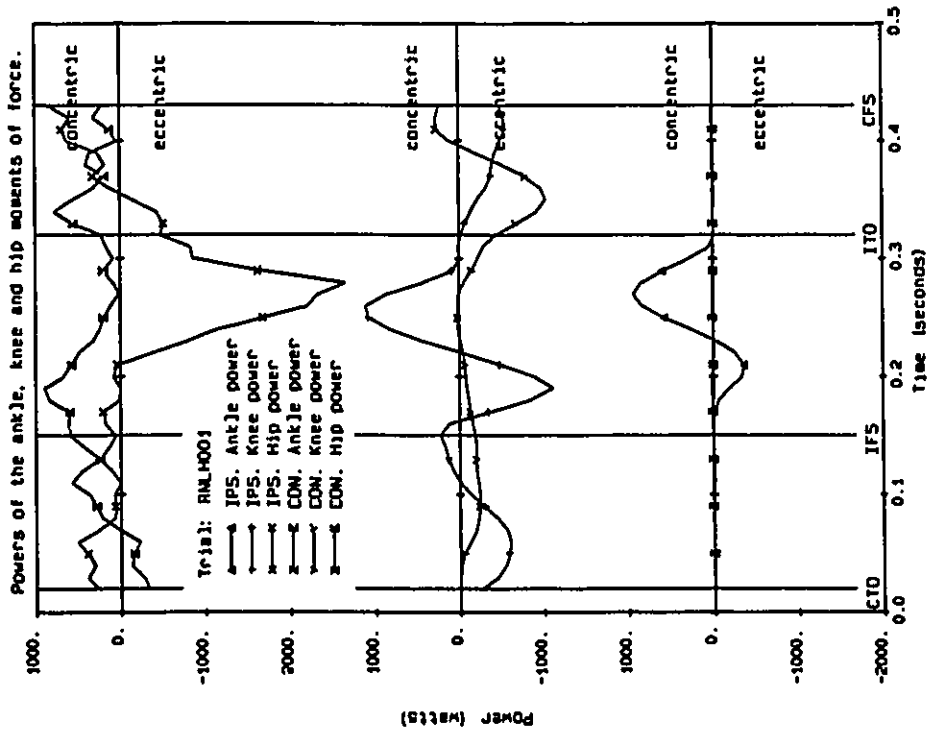
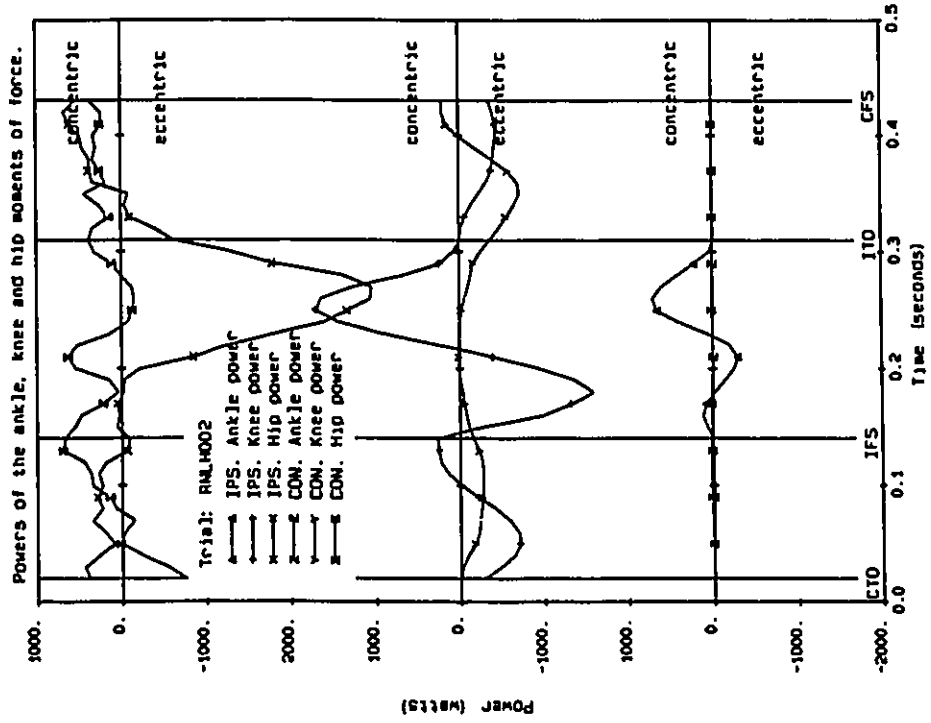


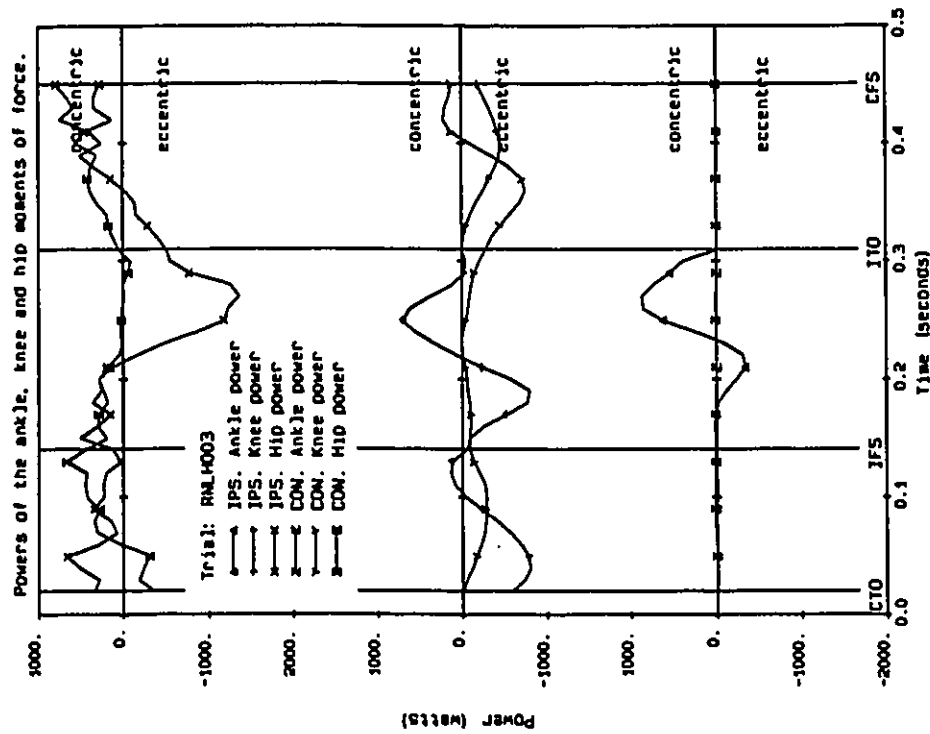
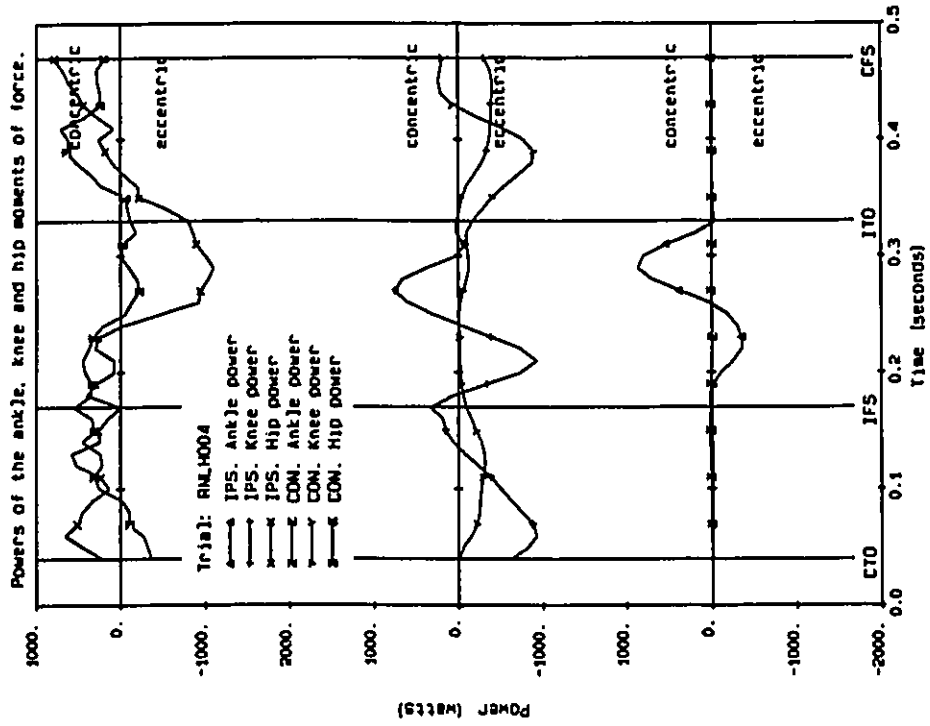


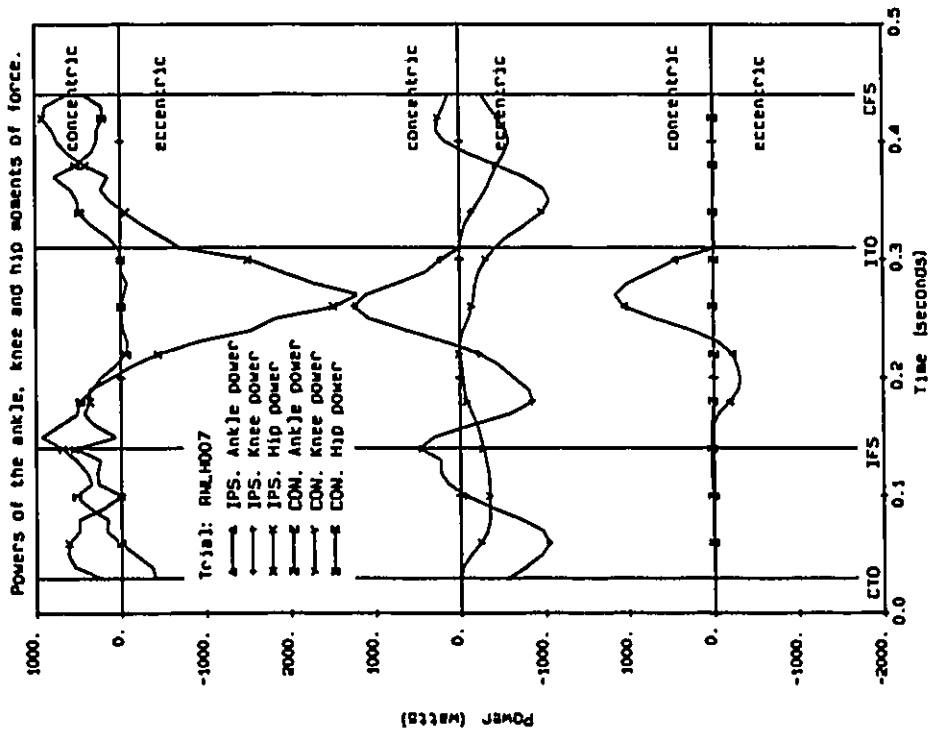
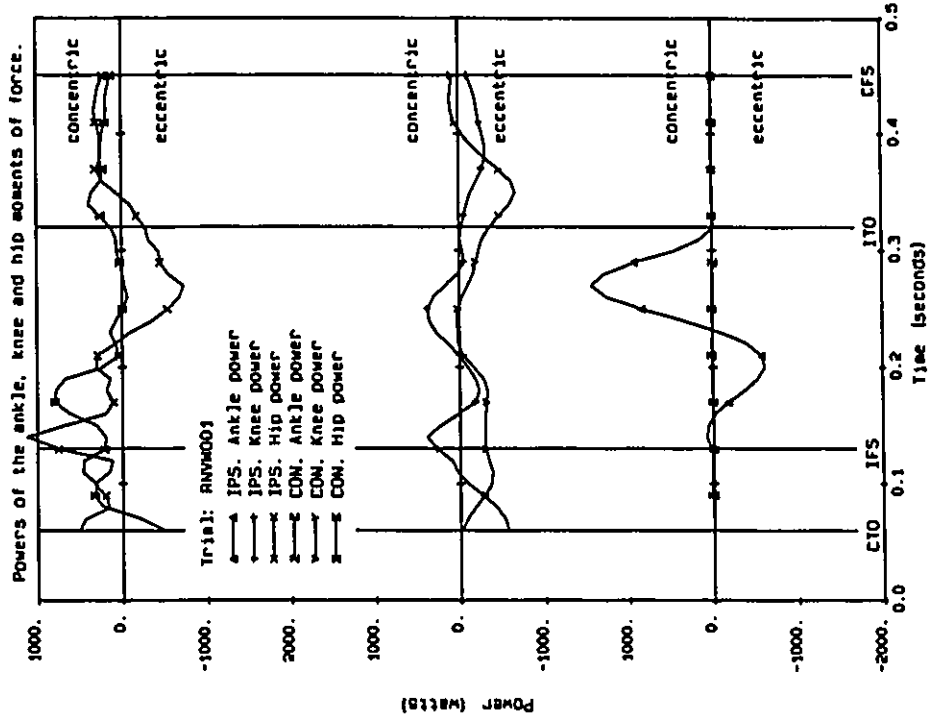


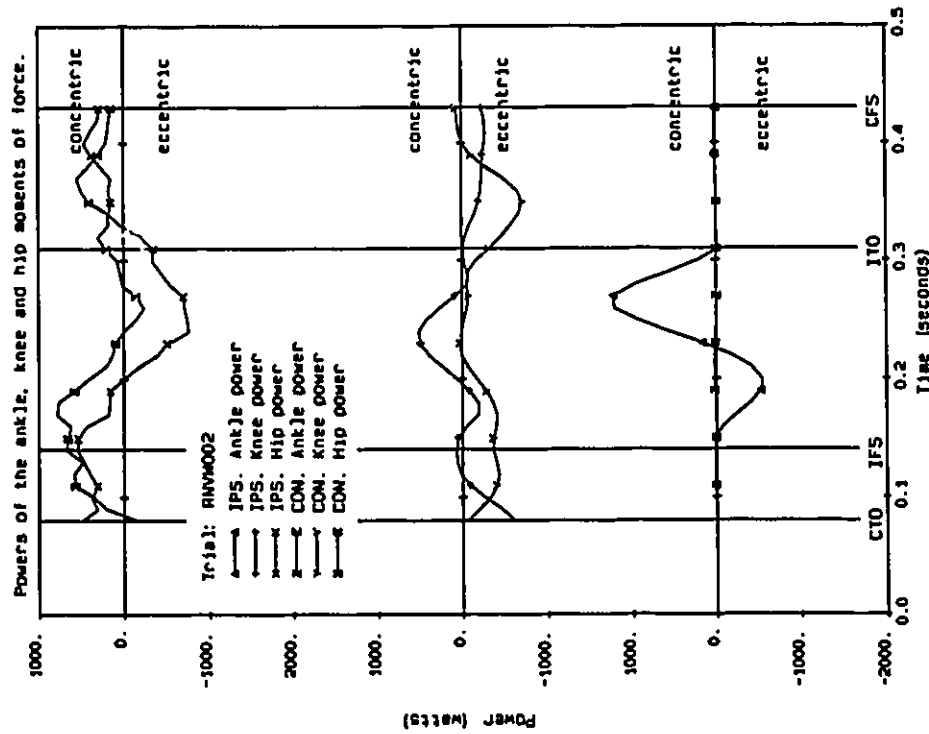
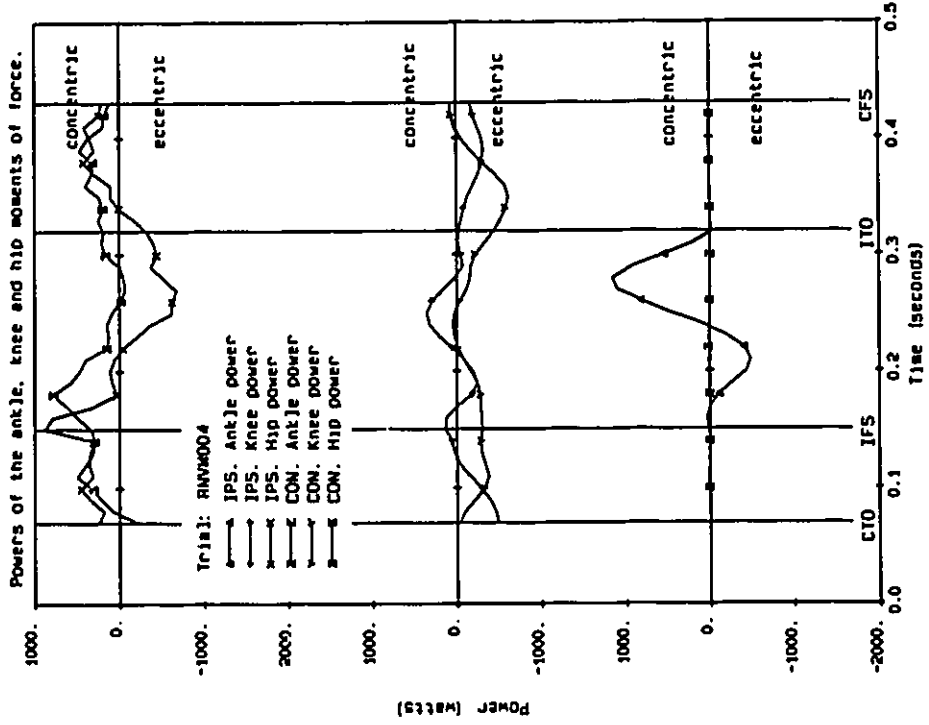


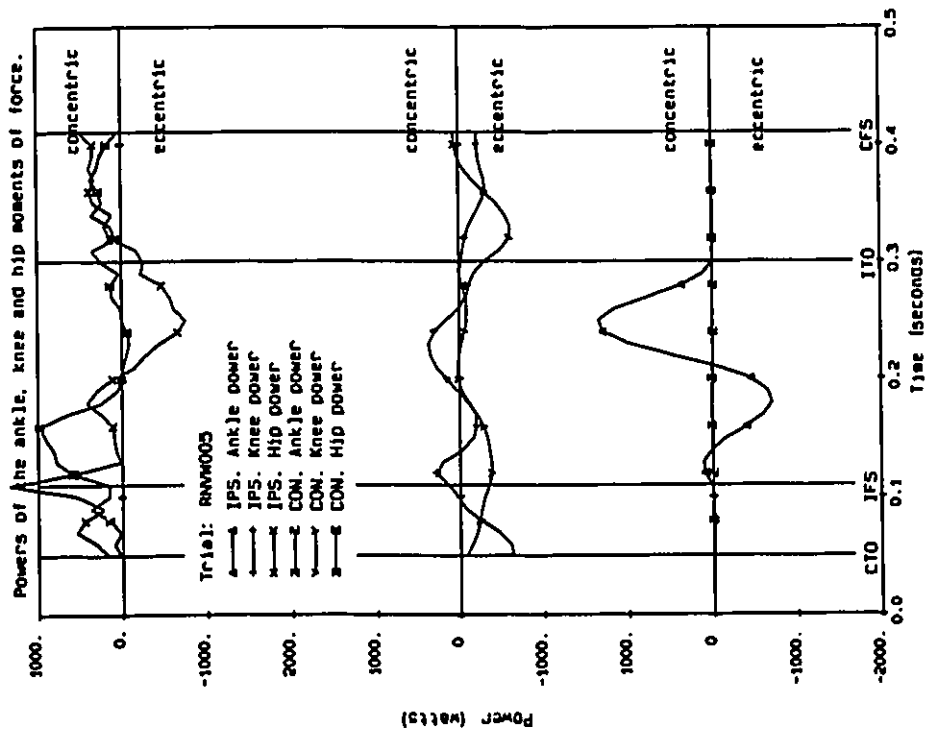
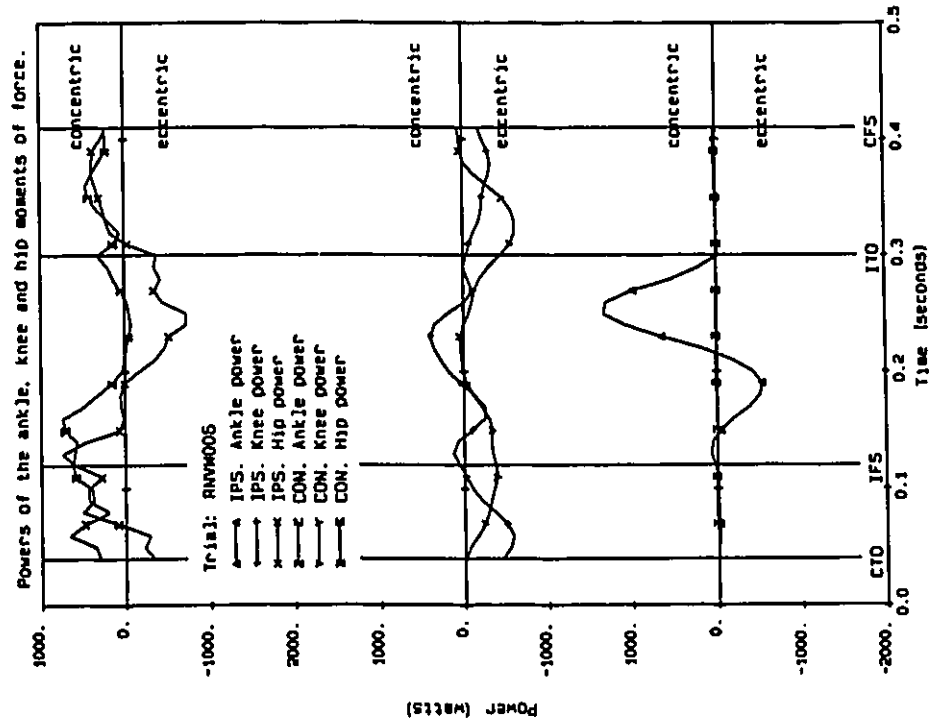


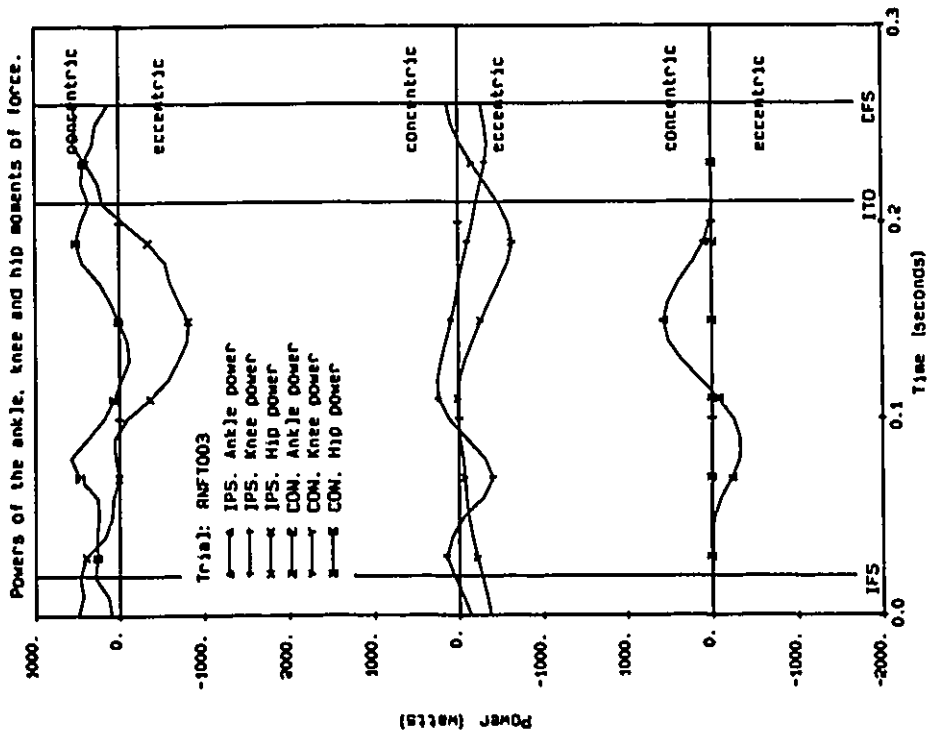
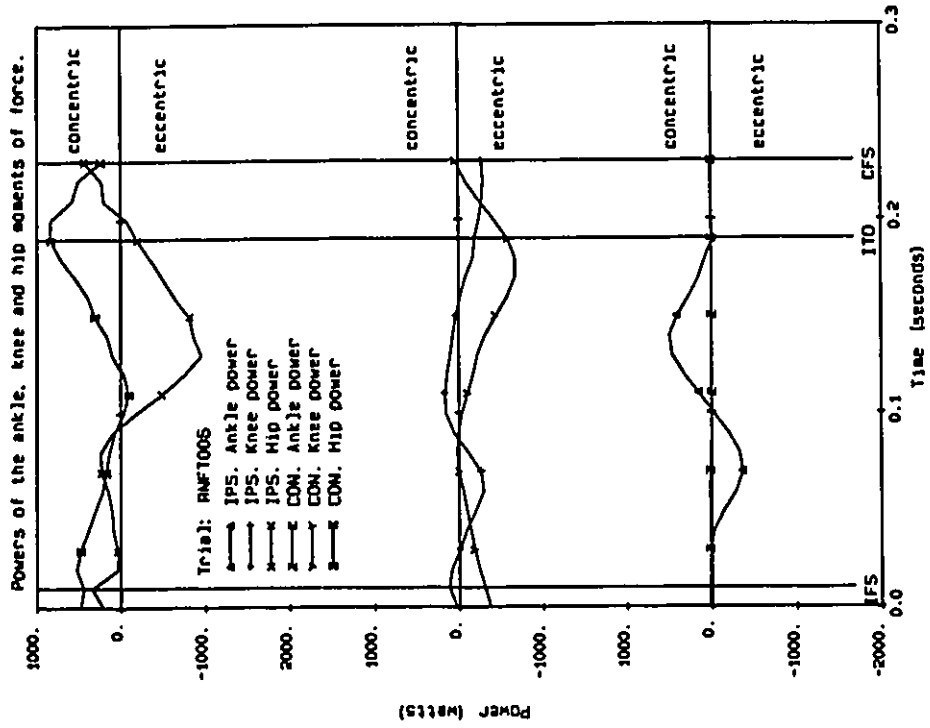


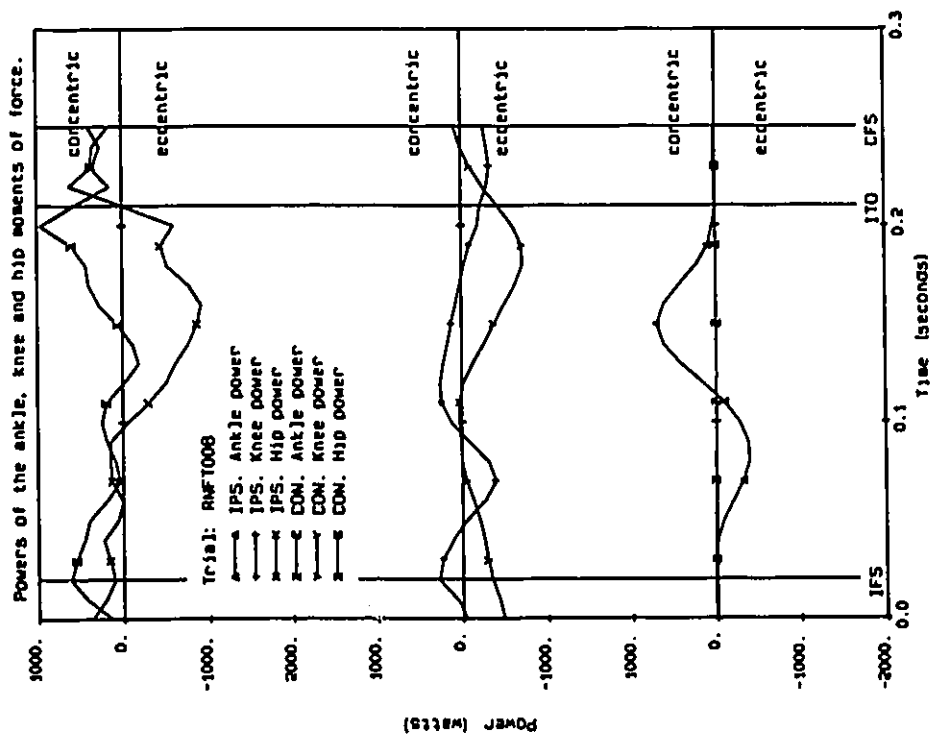
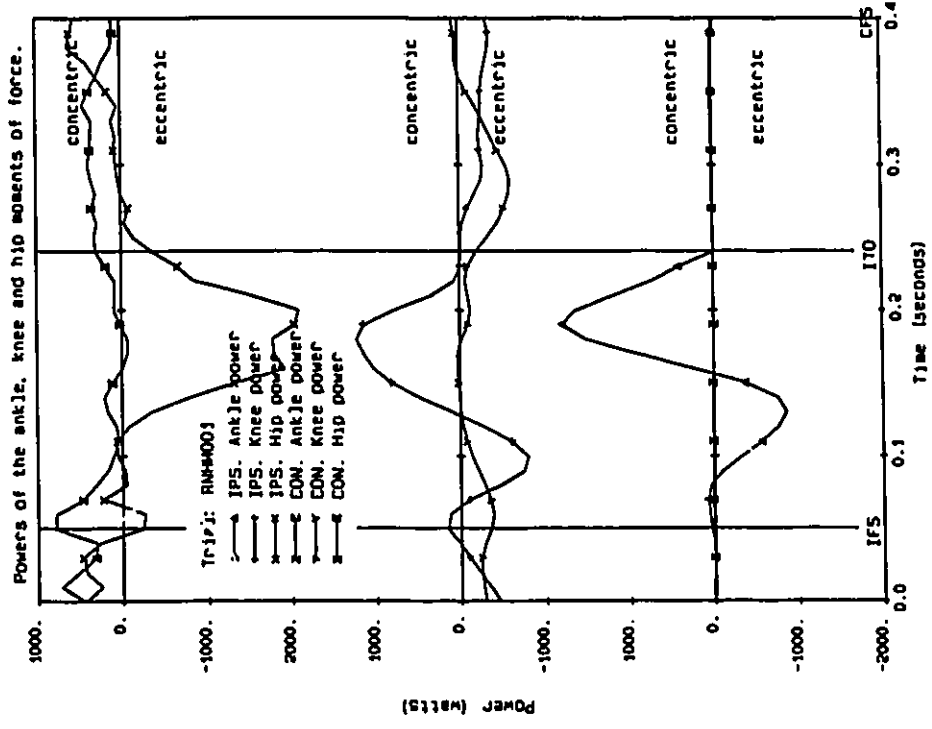


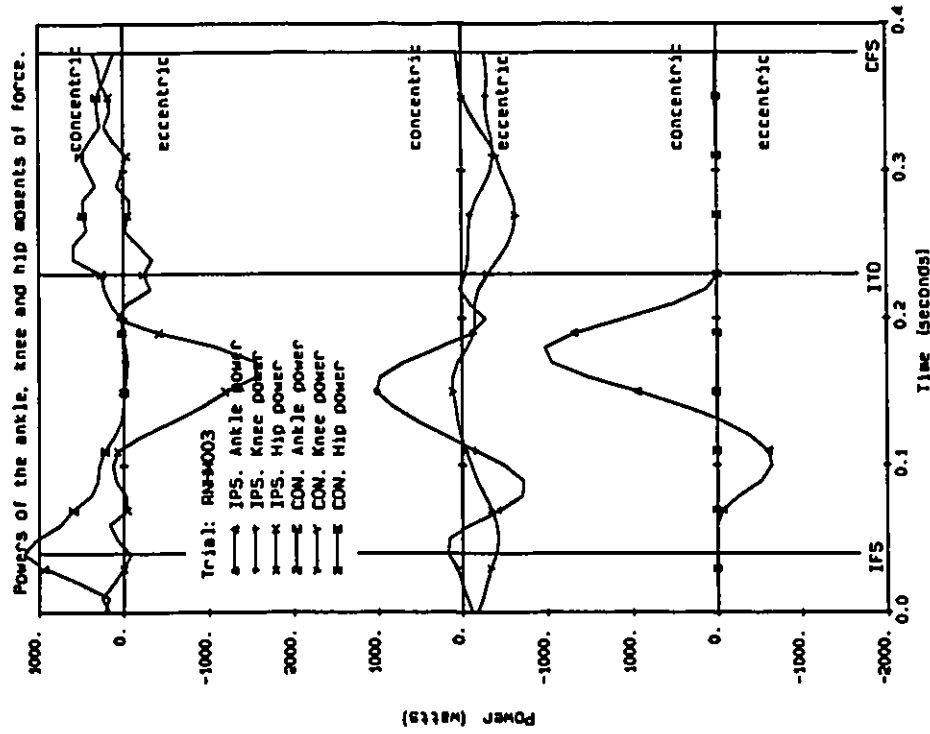
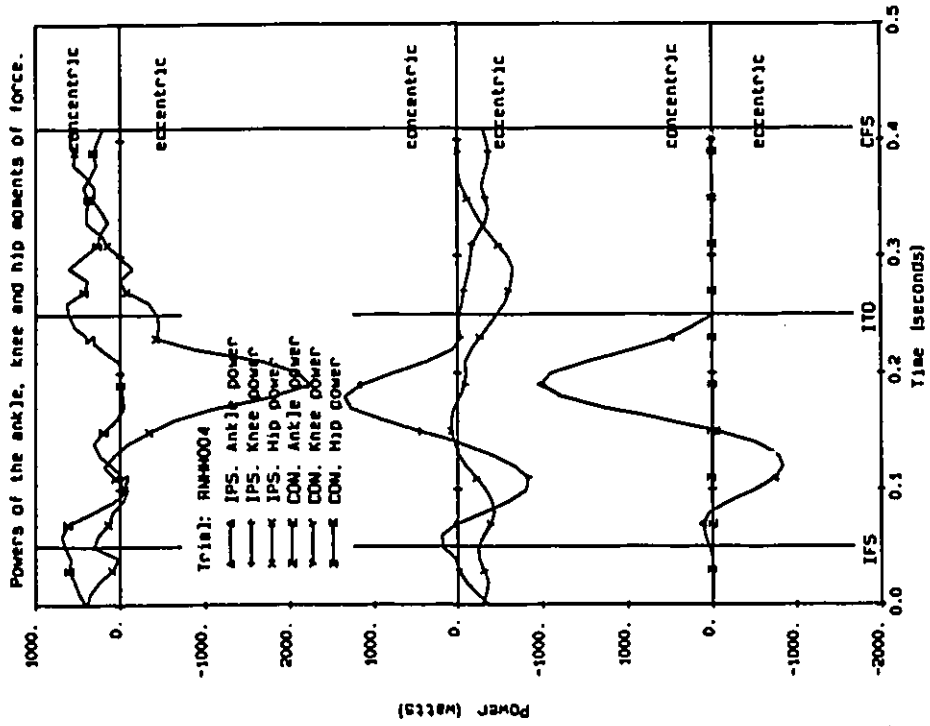


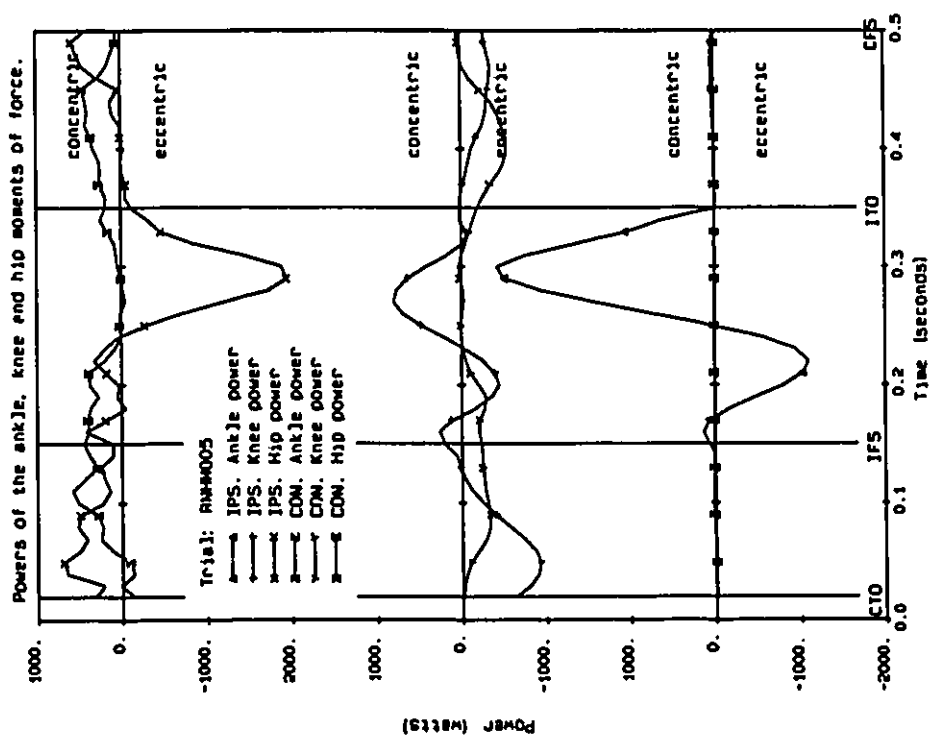
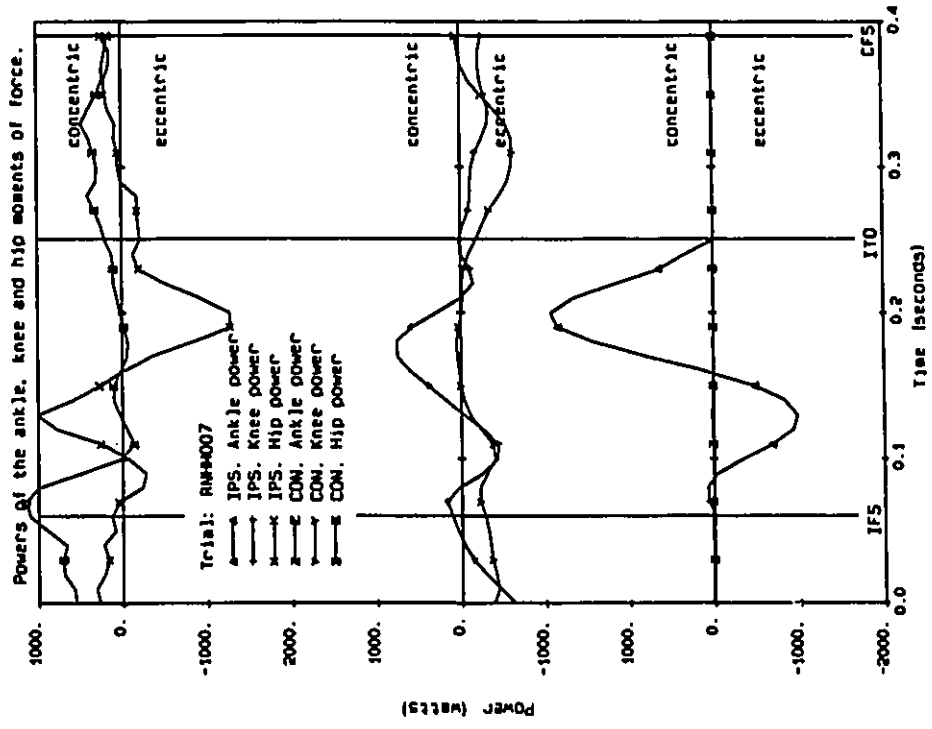


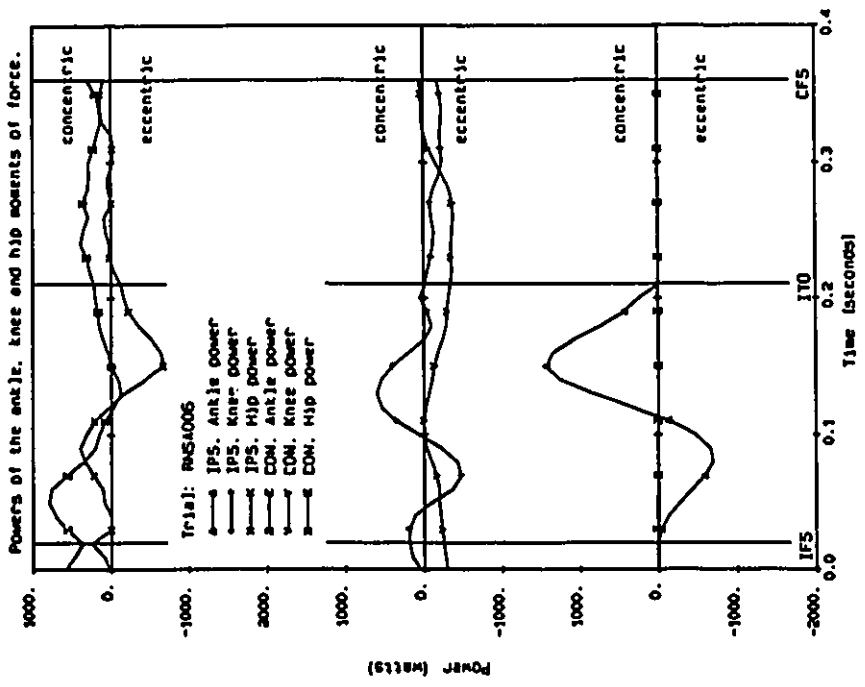
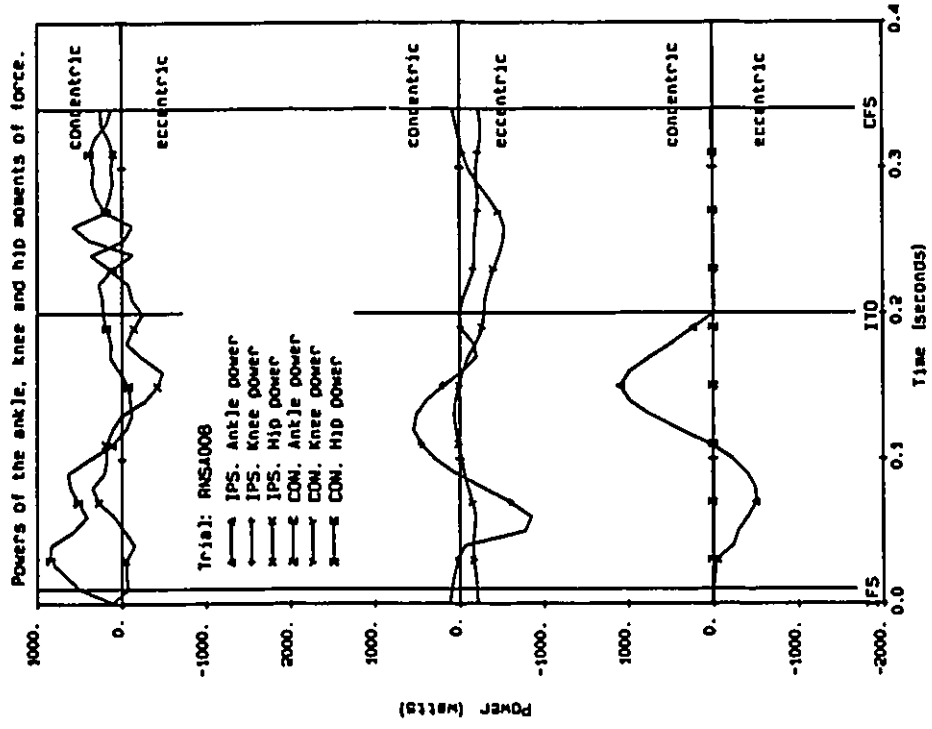


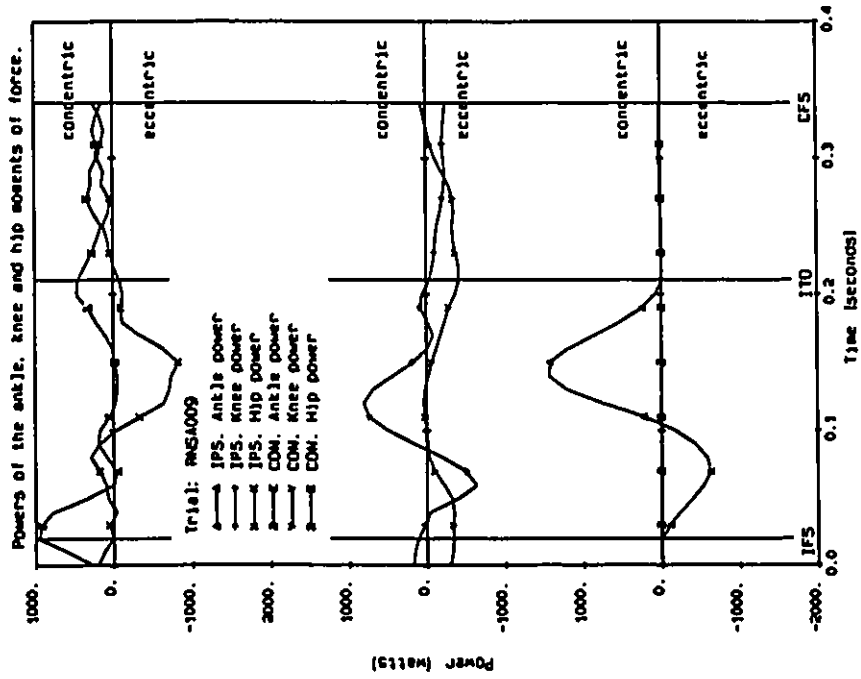
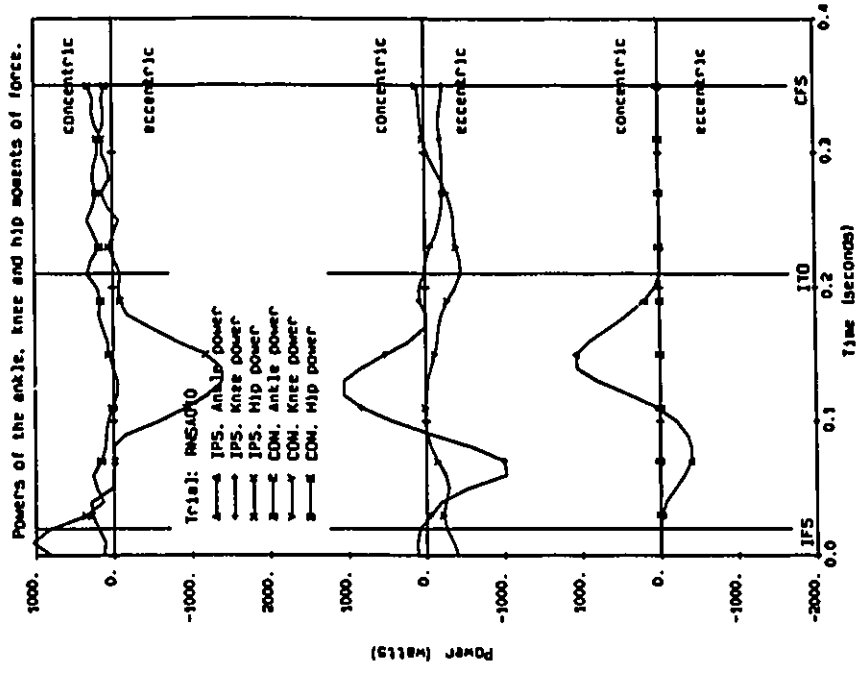


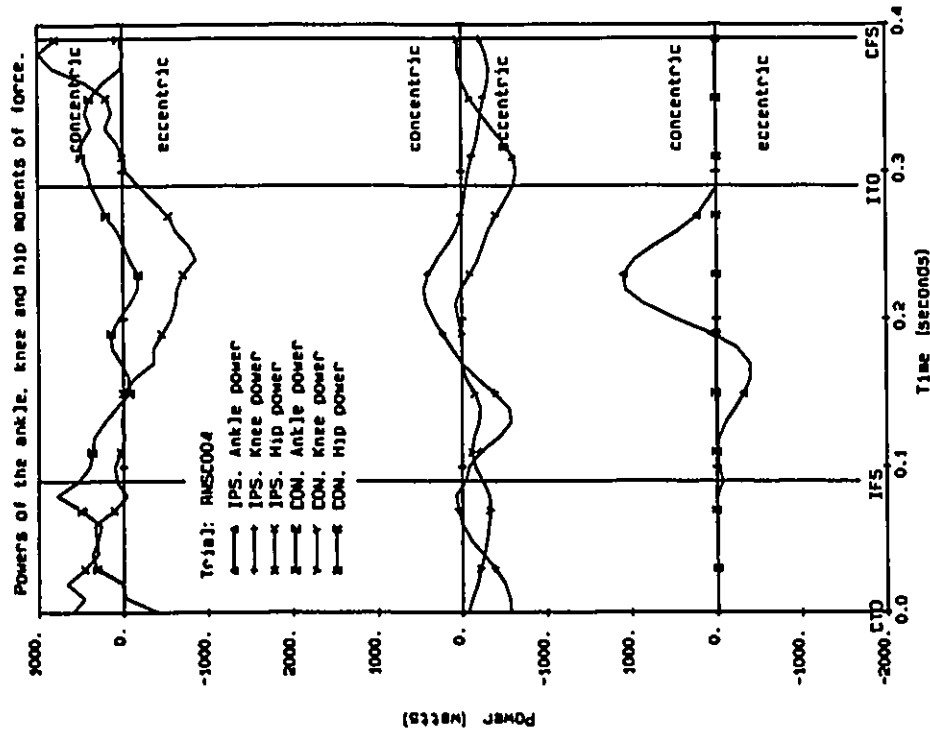
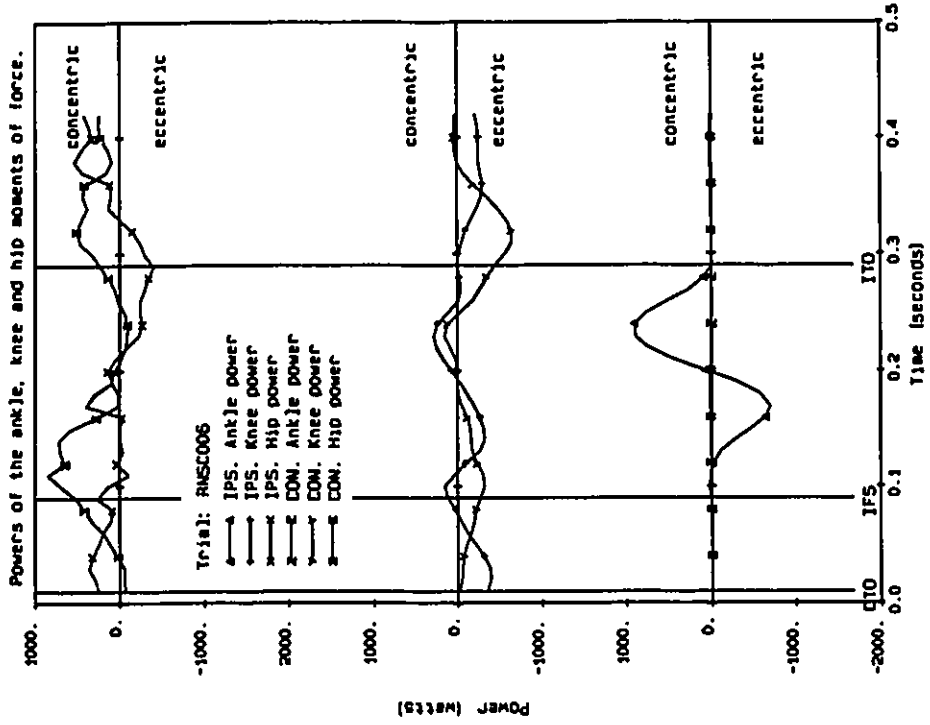


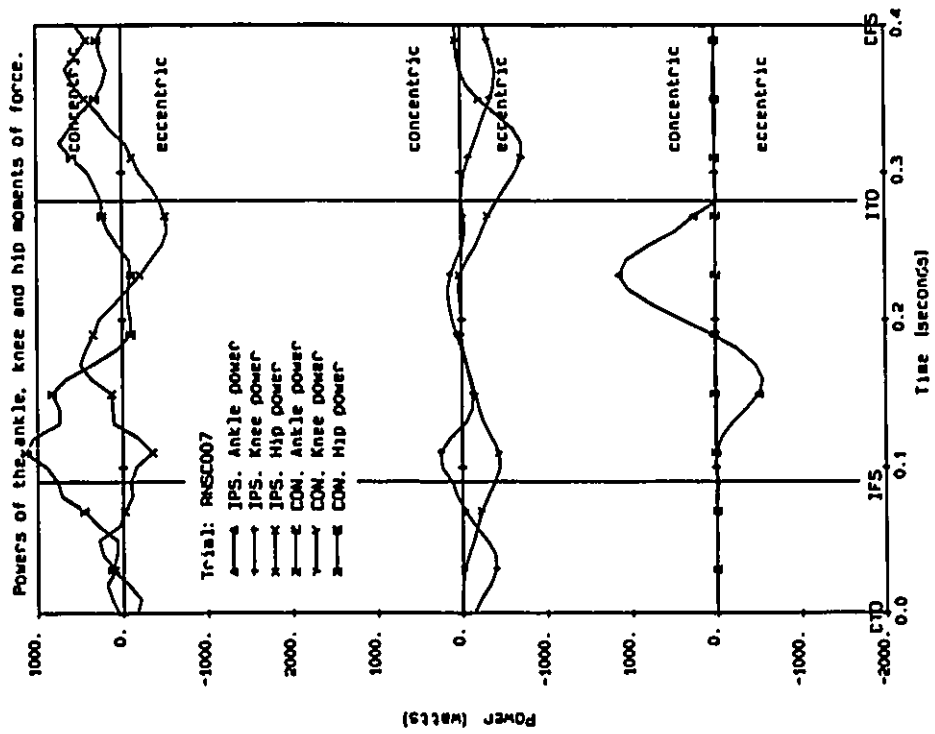
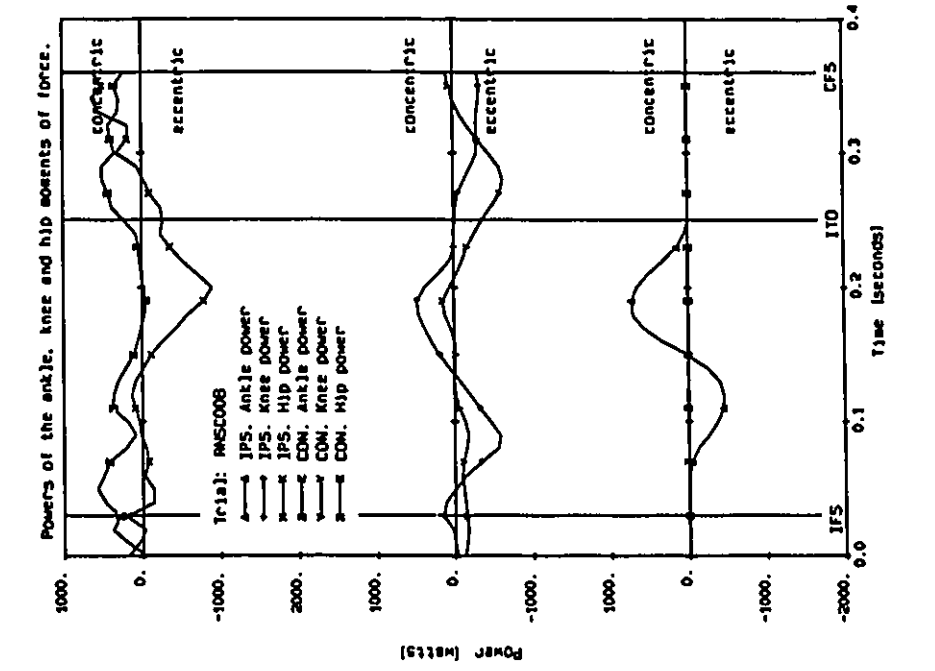


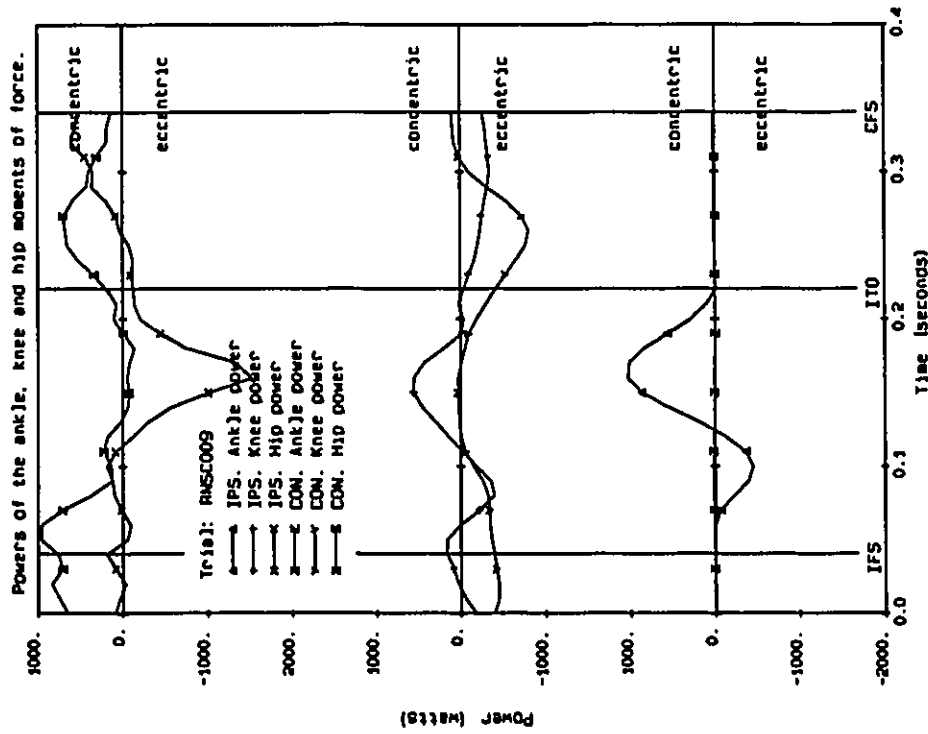
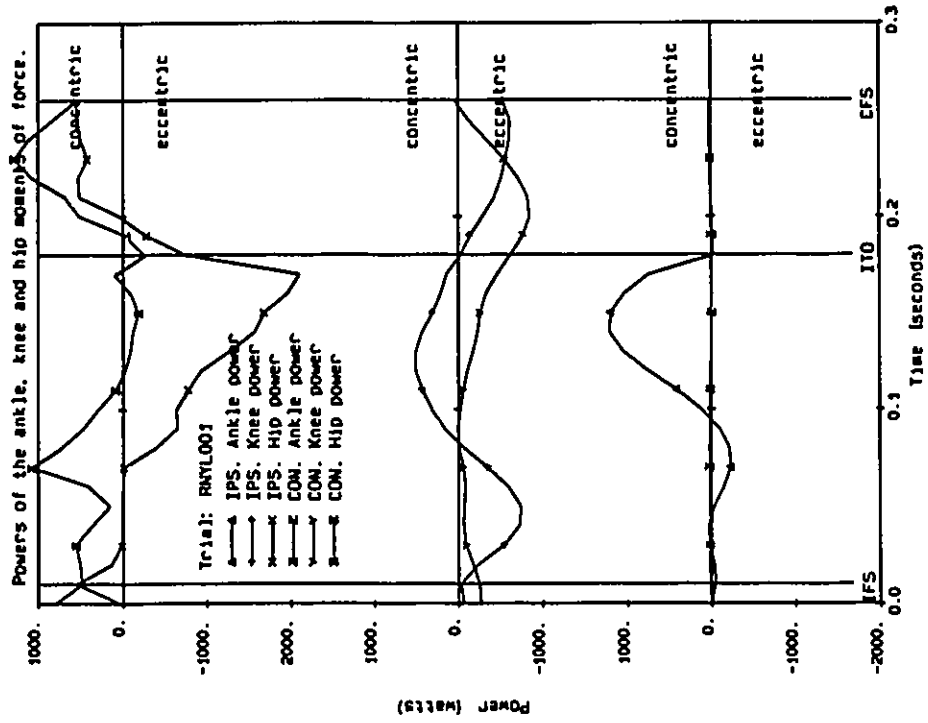


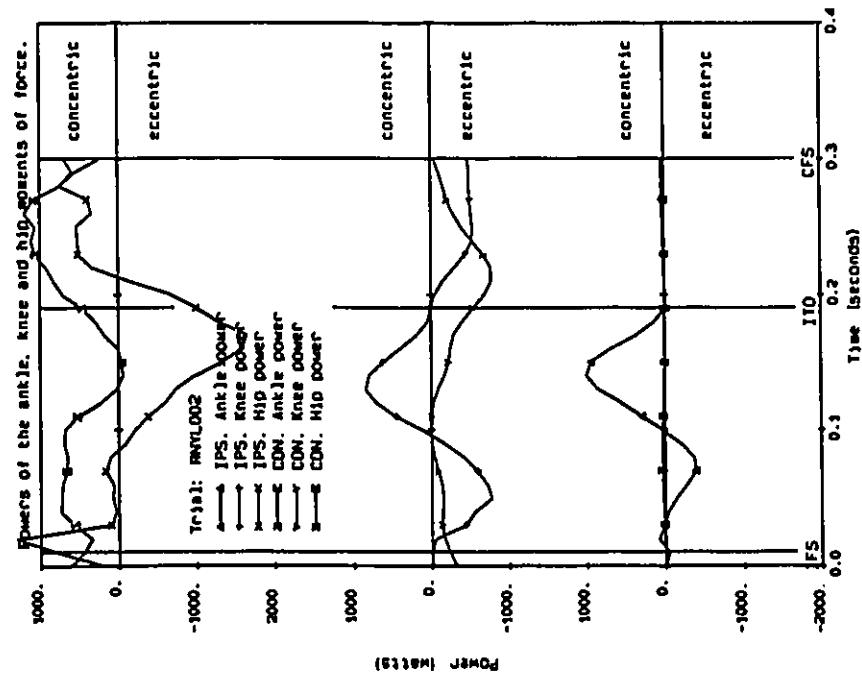
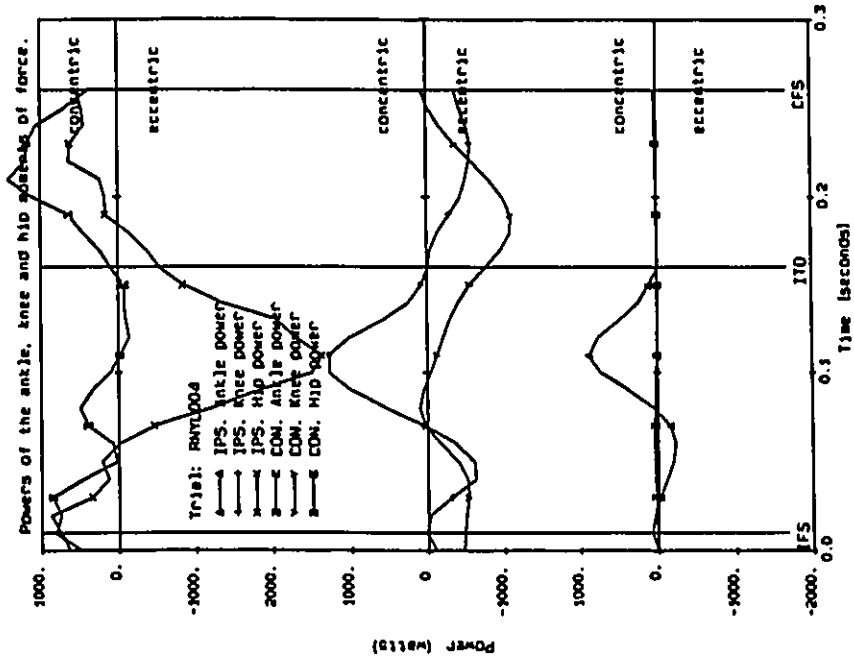


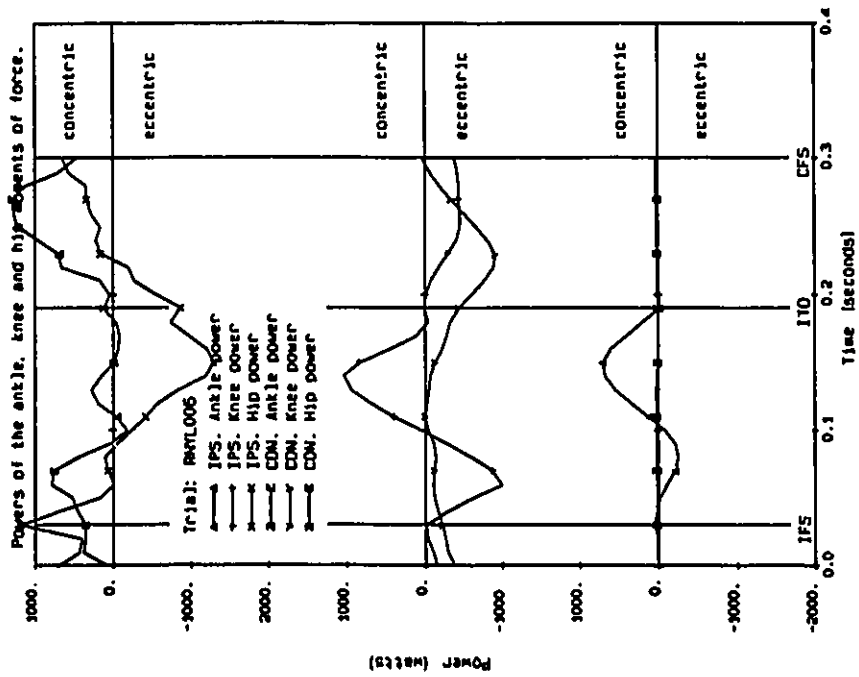
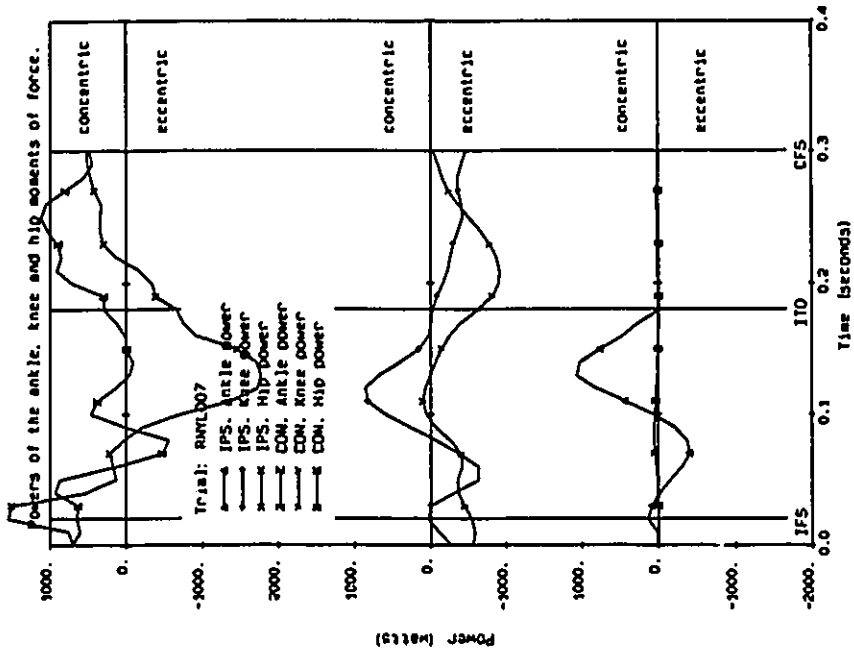












Appendix C: Consent Form

Information and Consent Form for the Study: Comparison of Methods for Calculating Internal Work of Running in Humans

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

Procedure: Anthropometric data (age, gender, height and weight) will be collected. You may be asked to remove some clothing or to wear clothing appropriate for running. Reflective markers will be attached to the clothing at joint centres of rotation. You will warm-up, and then be given as many practice runs as you like. You will then be asked to run five times across the force platform at your chosen speed (submaximal). You will run 7 to 10 metres for each trial, and each trial will be filmed. The test will take no more than two hours and will be completed in one session. You may refuse to take off your clothing or wear the clothing supplied or to perform the movements that the experimenter requests without penalty or discrimination.

Risks: There is minimal risk involved in this experiment. The physical risk factor is not greater than what would be encountered in your normal activities. Please notify the investigator should you experience any feeling of discomfort.

Anonymity: Each subject will be assigned an anonymous 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 (address below).

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 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:

Patricia A. Turnbull & Dr. Gordon Robertson
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University of Ottawa, Ottawa, ON, K1N 6N5
(613) 564-9105.

This study has been approved by:

Faculty of Health Sciences Human Research Ethics Committee Chair Frank Reardon
401 Smyth Road
Ottawa, ON, K1H 1M5
(613) 787-6726.

Appendix D: Review of Literature

Review of Literature

There are two distinct ways to calculate mechanical work. One way utilizes an energy approach based on anthropometrics and kinematic data while the other uses inverse dynamics and joint power production to compute the work done by the joint moments of force.

Calculating Mechanical Work (Energy Approach)

Historical Approaches. To this day, there is no consensus as to how to calculate mechanical work (Wells, 1988). All of the existing methods of calculating mechanical work have problems associated with them. In 1930, Fenn was the first to look at the flow of metabolic to mechanical energy. He used cinefilm data and summed the translational and rotational kinetic energies (KE) of each segment of a sprinter. He assumed that the kinetic work done was equal to the sum of all increases in the segmental KE curves. He also assumed the same for the potential energy (PE) curve and the potential work. Thus, Fenn's definition of mechanical work was the sum of all KEs plus the sum of all PEs. Unfortunately, this definition excluded two very important factors involved in mechanical work. The first factor is that energy is exchanged within segments and the second factor is that energy is exchanged between adjacent segments (Winter, 1978). Fenn concluded that the transfer of momentum and energy from one part of the body to another, did not seriously interfere with his values for the deceleration and acceleration of the limbs. Fenn also down played the importance of stored energy. This means that Fenn's calculations resulted in an overestimated of the mechanical work done.

Following World War II, Bresler and Berry (1951) and Bresler et al. (1957) developed equations for three-dimensional movement analysis. Unfortunately, these equations were only used in a two-dimensional (2D) study of amputee gait. Their equations can be used in planar studies of normal gait or running, but one must assume perfect frontal plane symmetry between the two lower limbs. Other assumptions employed by Bresler et al. would also have to be modified for the study of running (Winter, 1978). For example, rotational KE was assumed to be negligible which may not be true for running (Winter, 1978). Another problem associated with the Bresler et al. studies was that the head, arms and trunk (HAT) segment was not included in the data and, thus, the energy exchanges between these segments could not be obtained.

In the 1960's, Cavagna et al. introduced force plate analysis into the mechanical work problem. These researchers used the total body centre of gravity's (CG) kinematics to calculate mechanical work. This technique did not take into account reciprocal movements of the limbs or rotational KE of the lower limbs (Winter, 1978). According to Winter (1978), this approach produced about 40% error by not considering reciprocal movements and another 5% by neglecting rotational KE components (in slow movements such as gait). Thus, the assumption that the CG energy represented the sum of all the segment energies was in error and produced an under estimation of the work done. Another limitation to this approach was that it is not practical when analysing sporting events. It is not practical to place force plates all around a running surface and expect the runners to hit the plates every time around.

Another energy approach taken in 1969 by Gersten et al. assumed that energy information was available from the trajectory of the anatomical CG. A force transducer was

attached to the trunk and data were collected from it. This method only gave data about the segment that the transducer was attached. For instance, reciprocal arm movements require energy, but this approach could not take this into account. Winter (1978) estimated that this approach will produce up to 70% error.

In Norman, Sharratt, Pezzack and Noble (1976), the pseudowork approach was developed. Norman and colleagues put forth the problem that there were many values for efficiency of movement due to the variety of ways that the many researchers calculated it. Trying to solve this problem, they added yet another method. The model that they developed was similar to Fenn's (1930), excepting that it included all body segments. The total pseudowork done per stride was calculated as the sum of the absolute changes of each of the potential energy, translational kinetic energy and the rotational kinetic energy from frame-to-frame and segment-to-segment. The premise behind the absolute value was to account for both negative and positive work done. This model had one large flaw, similar to Fenn's, it did not account for between and within segment energy transfers; thus, the values obtained for total work were over estimated.

In 1980, Pierrynowski, Winter and Norman expanded the pseudowork approach to include these transfers. They also included all potential and kinetic energy components and both positive and negative work. Pierrynowski and colleagues were able to calculate total work, W_a (this was the same as Norman et al.'s total pseudowork done) and total work taking into account the transfers within and between segments (W_{wb}); this was also their internal mechanical work value. They were able to determine the work done by only within segments transfers and no between segment transfers (W_w). The mechanical efficiency of walking in this

study was 65%. This included positive and negative work as equal entities. This approach is called absolute work in the present study.

Calculating Mechanical Work (Power Approach)

Historical Approaches. It seems that the majority of the past studies concentrated on calculating mechanical work via the energy approach. The integral of mechanical power also gives us the mechanical work value. Elftman (1939a,b) was perhaps before his time in the calculations of mechanical power. He developed the first force platform capable of determining centre of pressure. From it he was able to calculate the force in three directions and the position of the ground reaction force. From there he used D'Alembert's Principle to calculate the forces and moments acting on the foot, leg and thigh. Elftman used inverse dynamics combined with cinefilm to calculate the rate of energy production across the joints by the moments of force. His equation was:

$$W_m = \int P_m dt(\text{joules})$$

P_m is the power generated across the joint by tissues such as muscle, tendon and ligament. It was obtained by multiplying the moment (M) by the angular velocity (ω) at the joint of interest. The work (W_m) is then obtained by taking the integral of the power.

Elftman recognized energy transfer, storage and dissipation. Elftman's hand calculations were very laborious but his technique was solid and could be computerized. This was done by Quanbury, Winter and Reimer (1975), who applied it to walking. They used more reliable kinematic data and also included a validation of the method by comparison with

the rate of change of segment energy (i.e., the derivative of the instantaneous energy). This instantaneous energy approach was expanded by Winter, Quanbury and Reimer in 1976 to include the leg and thigh during swing and by Robertson in 1977 to include the foot, leg and thigh during stance and swing during walking. Quanbury et al. (1975) stated that the most probable cause for the minor discrepancies between the two curves of work rate and power was because the power method required exact centres of rotation for each joint but these were unmeasurable by the instruments used.

The value of moment power analyses is that they can be done at any joint without having to worry about what is happening to the energy that is generated or absorbed (Winter, 1978). What we really have to know is the exact time when P_m is changing from positive to negative to calculate the positive and negative work (Winter, 1991). A correct ratio of negative to positive work savings must also be determined.

The major problem associated with this analysis is that it does not take into consideration the cocontraction of antagonist muscles. Thus, this method under estimates the positive and negative work of any given movement. The future of this research seems to be in the partitioning of the contributions of each muscle or muscle group to the net moment of the movement (Winter, 1991). It may be that EMG plays a role in solving this problem. If the relationship between force and EMG activity is ever determined, an extremely accurate model of work done, calculated via powers, could be achieved.

Recent Research. One of the most interesting studies to date was done by Chapman et al. (1987). The purpose of this study was to "determine the mechanical criteria that provide the basis for preferred long distance running style." The study consisted of one subject running in a preferred style and four modified styles. Chapman and colleagues assumed that the preferred style would also be the style that had the least cost. They used Pierrynowski et al.'s (1980) calculation (W_{wb}), Norman et al.'s (1976) pseudowork calculation (TPW also called W_n) and W_w that assumed transfer within but not between segments. They also included total body work (TBW), which is referred to here as absolute power. This was calculated as the sum of the time integral of the absolute value of each power at each joint. This study suggested that the W_{wb} measure was not an accurate reflection of muscular cost since all but one modified running style indicated a lower mechanical cost than the normal running style. The other equations also gave interesting results. The stiff-kneed running style scored lower in mechanical cost than all the other styles, with the normal style having the second lowest cost for the remaining equations. The authors suggested that the calculation of work done by absolute mechanical impulse appeared to be a better estimate than estimates based on changes in energy of the whole body. The mechanical impulse was calculated by taking the integral of the absolute moment at each joint and summing them across the joints.

Chapman et al.'s (1987) study, with this new method of calculating mechanical work, assumed that one style of running was the most efficient. How valid is this assumption? It would seem that over time, trained, experienced runners would have developed an efficient running style. This assumption seemed valid, but, in the study, the style of running that required the least amount of work was not the preferred style but a stiff-kneed style. This

"inefficient" style scored lowest for both the energy approach and the absolute power approach. Unfortunately, this study was limited by its very small sample size ($n=1$) and should not be accepted as conclusive.

Wells (1988) has also developed a slightly different approach to determining mechanical energy costs of human movement. In his study, he expanded upon and improved Elftman's (1940) approach to include two-joint muscles in the calculation of mechanical work. Elftman stated that a combination of one- and two-joint muscles still maintained some of the advantages of a three-joint muscle but also allowed individual movements even though the energy cost was sometimes duplicated by this arrangement.

In Wells' work, he used the power concept but called it joint-work. He developed an algorithm to define the contributions of one- and two-joint muscles. If a two-joint muscle was active, then the smallest muscle force required to service the joint moment of force, taking into account the lengths of the moments arms, was calculated. Then the one-joint muscles supplied the rest of the moments required at the other joints (Wells, 1988). With this approach, Wells noticed that often the one-joint muscle work was largely reduced or eliminated at certain phases of walking. He also noted that use of the two-joint muscles reduced the mechanical work compared to results of using only one-joint musculature. Another significant conclusion was that, the interchange of energy across joints reduced the mechanical energy requirement further. Overall, Wells (1988) found that the two-joint muscles gave a savings of about one quarter to one half of the maximum savings possible through interchange among all joints.

One set of studies that stands separate from all other studies was by Aleshinsky (1986a–e). In these studies, he examined the methods of determining mechanical work. In

part a, Aleshinsky proved that models that do not contain between and within energy transfers and models that look at internal work as changes of the energies of the links in their movement relative to the general centre of mass, such as the absolute work approach are incorrect. These models do not follow the laws of classical mechanics. They sum up positive increases and negative decreases to obtain the work done. In the following parts, Aleshinsky went on to discuss the concepts of internal and external work, the conservation coefficient, energy transfers within and between links and mechanical energy economy. Overall, Aleshinsky did support, mathematically, the total body work (TBW) approach taken by Chapman et al. (1987) and did not support the absolute work (W_{wb}) approach developed by Pierrynowski et al. (1980).

Critiques

In a paper by Williams and Cavanagh (1983), a thorough discussion of the calculations of mechanical power output during distance running was undertaken. They stated that the changes in KE were derived from three major sources: 1) muscular activity, 2) release of energy previously stored in the elastic tissues and 3) transfer of energy between segments. Their research also examined flaws in the calculations of mechanical work of the five methods presented. Williams and Cavanagh (1983) criticized Winter's (1978, 1979) method of calculating mechanical work. They stated that a major problem with his scheme was that it allowed segmental transfer of energy between any two segments in the body. Accordingly, a plantar flexion of the right foot would be cancelled by an equal but opposite movement of the right hand. Winter's equations assumed, for example, that simultaneous generation at the foot

and absorption at the hand occurs. Chapman et al. (1987) noted this by explaining that the absolute work equation for W_{wb} does not take into account differential muscular costs for similar amounts of between segment energy transfers. Another criticism of the absolute work method concerned two different roles of negative power (Williams and Cavanagh, 1983). The method does not let some of the negative power generated be included due to between segment transfers (Williams and Cavanagh, 1983) as explained in the above example. Also, in Winter's earlier work (1978) he did not account for the different metabolic costs associated with concentric vs. eccentric work. Winter (1979) did address this fact later and noted that his equations would allow separation of the two types of work. Williams and Cavanagh (1983) attempted to account for the differences in positive and negative work (both passively and actively), the effect of stored elastic energy and the transfer of energy between and within segments. For the latter part, the authors set up strict rules for when transfer should be included and when it should not. Another difference in this study compared to previous ones was that this study used 3D coordinates to study running and did not have to rely on the assumption of symmetry between legs.

Other Considerations when Calculating Mechanical Work

Elastic Storage. Many researchers have stated that one of the major problems with determining mechanical work is amount of storage and release of elastic energy in complex human movements. At the moment, there is no way of determining these values. There is also the question of whether or not certain muscles store energy at different rates. Different

muscles may have different optimal storage rates dependent on a number of factors. The rate may be influenced by fibre type (fast twitch vs. slow twitch), muscle architecture and velocity of contraction, and crossbridge phenomenon. Furthermore, Funato et al. (1985) have suggested that mechanical efficiency is related to the frequency of the exercise cycle and not by the amount of work done. For instance, if an individual is doing a repetitive vertical jump, then the faster he/she jumps, the more stored energy he/she will be able to use from the counter-movement (eccentric contraction). Fukashiro et al. (1983) stated that there is an optimal negative power that should be exerted to get optimal usage out of the stored energy when performing a vertical jump. Auri and Komi (1987) stated that 1) elastic properties influence efficiency of locomotion and 2) that the crossbridge mechanism in fibre types plays a definite role in the utilization of elastic energy.

There is no direct way of determining the contribution of elastic energy to the movement. One study involving knee bends, has suggested that the contribution may be as much as 47–62% (Cavagna et al., 1964).

Resonance of the Body. Denoth (1985) has proposed that a resonance phenomenon may exist. With resonance the energy expended at optimal frequency performances may be less than energy expended at other frequencies (Denoth, 1985). Distance runners tended to be more efficient at slower running speeds compared to sprinters who tended to be more efficient at higher running speeds (Kaneko et al., 1985). This may be a factor of fibre type. Sprinters have more fast twitch fibres, whereas, distance runners have more slow twitch fibres. Therefore, for individual performances, fibre type may be an influencing factor in natural frequency of the body.

Cocontractions. In an intact human, only the net muscle moment can be determined; thus, if there is cocontraction, the efficiency will be over estimated. Cocontractions may be a source of inefficiency but may be a part of a safety mechanism. If the body is in danger of injuring a muscle by overstretching, this mechanism may be activated to prevent damage. Cocontraction is also used in situations of instability. Thus, over estimation of efficiency is also seen when examining non-maximal activities.

Isometric Contractions Against Gravity. In some situations, muscles must hold the limbs statically against the force of gravity. This rarely occurs in normal movements but occurs many times in pathological movements. These types of movements are beyond the scope of this report. Presently, it is impossible to determine the amount of energy required to perform these contractions (Winter, 1991).

Positive vs. Negative Work. It is a generally recognized fact that negative work has a lower physiological cost compared to positive work. What the ratio between the two works is not yet known. In the literature it ranges from 1:6 to 1:2 (Abbott and Bigland, 1953; Passmore and Durnin, 1955; Magh et al., 1965; Margaria, 1968; Norman et al., 1976). It is possible that the ratio is different for different fibre types (FT, ST), muscle types (pennate, fusiform etc.) and different movements or types of activities (aerobic, anaerobic). Fortunately in this study this is not an issue. The difference in cost associated with positive and negative work is only of interest if the physiological cost (oxygen uptake) is being determined. In this study, only the work output is being looked, so one joule of positive work equals one joule of negative work (Caldwell and Forrester, 1992). So the ratio of positive to negative work will be 1:1.

Summary

Both energy and power approaches have provided researchers with many tools with which to quantify the mechanical cost of movement. Each approach has its flaws but the only approach that has been validated mathematically is the absolute power method. Unfortunately, this method has only been looked at in one study that consisted of only one subject. Clearly there is a need to examine this method more closely and compare it with the more commonly used absolute work approach. The proposed study will contrast the two approaches. It will also compare two vastly different groups of runners and determine if differences in internal biomechanical cost (IBC) calculated by the absolute power approach can be ascertained.

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