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MECHANICAL WORK: AN ANALYSIS OF ITS APPLICATION TO THE STUDY OF HUMAN PERFORMANCE

By

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ABSTRACT

MECHANICAL WORK: AN ANALYSIS OF ITS APPLICATION TO THE STUDY OF HUMAN PERFORMANCE

By

Raymond Robert Brodeur

The purpose of this thesis was to investigate the methods for calculating mechanical work as they apply to the study of human efficiency. In the study of human efficiency there is no agreed-upon method for determining the mechanical work done by the body. A model for calculating the total work done by all muscle moments of the body for any given event was developed and compared analytically to previous methods. Methods which use the change in segmental energy to calculate mechanical work were shown to be inadequate for calculating muscle moment work. The results show significant differences between the muscle moment model and energy methods for calculating total body work.

In addition, the work done on each body segment and the work done by the joint muscle moment of each joint on the left side of the body were investigated for the stance phase of running. The results of the segmental work and the joint work were similar to the results of other studies.

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CHAPTER I

INTRODUCTION

The study of human motion efficiency is a difficult and complex task. In engineering terms, efficiency is defined as the ratio of the total mechanical work done by a machine to the total energy of the fuel consumed by the machine. Thus, an extension to measure the efficiency of human movement would be to determine the ratio of the total mechanical work done by the muscles of the body to the total metabolic energy consumed.

Unfortunately, there are a myriad of complicating factors. Methods of measuring metabolic energy usually consist of determining oxygen uptake. However, there is difficulty with differentiating the component of metabolic energy expended to perform the task being measured from the component of metabolic energy used for resting respiration. Metabolic energy calculations are further complicated by the body's ability to use anaerobic respiration.

The methods for determining mechanical work done by the muscles of the body are also wrought with problems. Several investigators use the change in segmental energy as a means of calculating mechanical work. However, the change in the energy of a limb segment is not necessarily indicative of the work done by the muscles attached to the limb.

In addition, the calculation of muscle efficiency is complicated by the fact that metabolic energy is expended both when positive work is done by the muscle and when negative work is done on the muscle. However, negative work is more efficient than positive work as it requires less metabolic energy. Metabolic energy is also expended during isometric contractions; a time when the muscle is doing no measurable mechanical work. To complicate matters further, muscle tissue has an elastic component that can be used to reduce the metabolic energy required when put through a negative to positive work cycle.

In the study of human performance, investigators calculate mechanical work from either kinematic or kinetic data. The advantage of using kinematic data is that only cinematic film and anthropometric measurements are needed. The segmental energy can be calculated, and thus the mechanical work done on each segment can be determined from the change in segmental energy. Most investigators prefer to use the kinematic method, since data collection is simpler.

Mechanical work can be determined directly from kinetic data, however, this type of data is more difficult to obtain. External forces must be measured or calculated, thus requiring additional equipment, such as force plates. This additional equipment can be a limiting factor and may restrict the feasibility of many studies. But, by obtaining kinetic data, both the work done by the joint reaction forces and the work done by joint muscle moments can be determined. Thus, with this knowledge, an investigator can determine the total work done on any body segment as well as the work done by individual joint muscle moments.

The problems and disagreements in the literature arise when using changes in segmental energy to determine the total work done by the muscles of the body. The major problem arises when researchers try to accommodate for the muscle expending metabolic energy during both positive and negative work. Because of this limitation, the mere summing of segmental energy changes is not adequate for determining total muscle work. As a result, several researchers have developed methods for summing segmental energy changes which try to account for this limitation. Unfortunately there has been no agreement between the methods and it is unclear as to what these methods are physically related to.

The purpose of this thesis was to investigate the methods for calculating mechanical work as they apply to the study of human efficiency and to develop a model for calculating total muscle moment work. The analytical methods investigated the problem of trying to determine muscle work from segmental energy changes. The physiological problem concerning the fact that metabolic energy is required during both positive and negative muscle work is also addressed.

Since several of the papers reviewed in this thesis are concerned with determining muscle work from segmental energy changes, the literature review included a background section which reviews the relationship between mechanical work and energy. In addition, several investigators discuss muscle power and/or the rate of work done by muscle; therefore, the relationship between power, work, and energy has also been discussed in this background section.

CHAPTER II

LITERATURE REVIEW

2.1 Mechanics Background: Work, Energy, and Power

In rigid body mechanics the relationship between work and energy (16) is:

$$(1)\quad W_{12} = \sum_i \int_1^2 \mathbf{F}_i \cdot d\mathbf{s}_i = \sum_i \int_1^2 m_i \mathbf{a}_i \cdot \mathbf{v}_i dt = \sum_i \int_1^2 d(1/2\ m_i v_i^2)$$
$$= \sum_i 1/2\ m_i (v_{i2}^2 - v_{i1}^2)$$

where: $\mathbf{F}_i$ is the force acting on the i^{th} particle of the rigid body

$d\mathbf{s}_i$ is the infinitesimal distance through which each force, $\mathbf{F}_i$, travels.

m_i is the mass of the i^{th} particle of the rigid body.

$\mathbf{v}_i$ is the velocity of the i^{th} particle relative to a fixed reference frame.

W_{12} is the work done by all forces acting from point 1 to point 2.

Thus $W_{12} = KE_2 - KE_1$

where KE is the kinetic energy ($KE = 1/2 \sum_i m_i v_i^2$).

If the velocity $\mathbf{v}_i$ for each particle is written relative to the center of mass velocity, then:

$$(2)\quad KE = 1/2\ M\ v^2 + 1/2 \sum_i m_i\ v_i'^2$$

where: $M = \sum_i m_i$

$\mathbf{v}$ is the velocity of the center of mass.

$\mathbf{v}_i'$ is the velocity of the i^{th} particle with respect to the velocity of the center of mass $(\mathbf{v}_i = \mathbf{v} + \mathbf{v}_i')$.

In planar motion the term $1/2 \sum_i m_i v_i'^2 = 1/2 I\omega^2$ where "I" is the moment of inertia about the axis of rotation, and ω is the angular velocity of the rigid body.

The work done by gravity on a rigid body can be written as:

$$(3) \quad W_{12}^{(g)} = \sum_i \int_1^2 \mathbf{F}_i^{(g)} \cdot d\mathbf{s}_i = -\sum_i \int_1^2 m_i \mathbf{g} \cdot d\mathbf{s}_i = \sum_i m_i g\, h_i \Big|_1^2$$

where $\mathbf{F}_i^{(g)}$ is the force of gravity and h_i is the height of the i^{th} particle. $\mathbf{F}_i^{(g)}$ is a conservative force equal to $m_i\mathbf{g}$ where $\mathbf{g}$ is the acceleration of gravity. If h_i is written in terms of the height of the center of gravity, then:

$$(4) \quad W_{12}^{(g)} = M\, g\, h \Big|_1^2 + \sum_i m_i\, g\, h_i' \Big|_1^2$$

where h is the height of the center of mass and h_i' is the height of particle "i" relative to the center of mass $(h_i = h + h_i')$. Since the body is rigid, work done by the internal potential forces sums to zero, thus the term on the right is zero and:

$$(5) \quad W_{12}^{(g)} = M\, g\, (h_2 - h_1) = PE_2 - PE_1$$

where PE is the potential energy.

Since the focus of discussion in several of the papers reviewed in this study was on the rate of work and/or the power generated by muscle, it is important to briefly discuss the controversy over the definition of power. If power is defined as the rate of change of kinetic energy (17), then:

$$(6) \qquad \int_1^2 P \, dt = KE_2 - KE_1$$

where P is the power. This is essentially a scalar first integral of the motion. Several introductory texts in dynamics (Meriam (26)) define power to be:

$$(7) \qquad P = \mathbf{F} \cdot \mathbf{v}$$

and

$$(8) \qquad P = dE/dt = d/dt(KE + PE) = dW/dt$$

where: dE/dt is the rate of change of energy ($E = KE + PE$)

dW/dt is the rate of work being done.

However, other authors (Singer (33) and Harris (19)) discussed power as either an average power or an instantaneous power:

$$(9) \qquad P_{ave} = \text{work/time}$$

$$(10) \qquad P_{inst} = \mathbf{F} \cdot \mathbf{v}$$

Trusdell and Toupin (34) stated that there is no agreement on what "the" flux term is for mechanical energy.

The authors reviewed within this thesis defined power to be:

$$(11) \quad P = \mathbf{F} \cdot \mathbf{v} = dE/dt = dW/dt$$

In light of the above controversy, the definition given by equation (11) will not be challenged. Any further argument concerning power is beyond the scope of this thesis.

2.2 Calculation of Human Work from Potential and Kinetic Energy

Most researchers prefer to calculate the mechanical work of human motion from changes in kinetic and potential energy. This is an understandable choice from the point of view of data collection and analysis. Velocity data and anthropometric measurements are all that are necessary. Thus most early work used energy as a means of calculating mechanical work.

Fenn (11) analysed the work done in sprint running. He was the first investigator to accurately study the mechanical work done on each body segment by determining the change in the segmental kinetic and potential energy. It must be pointed out that Fenn did not calculate the work or the potential energy relative to a fixed frame of reference, the work done on each segment was calculated with respect to the whole body center of gravity. This type of analysis is referred to in the literature as "internal work".

In order to account for the physiological properties of muscle, Fenn calculated the total work done by summing the increase in kinetic energy of each segment and the increase in potential energy of each segment (relative to the whole body center of gravity). The negative work done on the segments was not used in his analysis. The sum of the segmental work was the total "internal" work as calculated by Fenn.

Fenn (12), used the data from his previous study (11), and calculated the work done on the center of gravity of the body by calculating its changes in potential and kinetic energy. This method is termed "external" work in the literature. The total mechanical work is then "internal" work plus "external" work.

Cavagna and co-workers (2-6) further investigated the concept of "internal" and "external" work. "External" work was determined by using a combination of force plate and accelerometer data. Their emphasis was on the comparison between changes in potential energy (W_v, for vertical work against gravity) to the changes in horizontal kinetic energy (W_f for work done to change the forward velocity of the body). It must be pointed out that this type of comparison has no physical meaning. Work is a scalar quantity, thus to compare "vertical work" to "horizontal work" (treating work as a vector) is not necessarily indicative of work done by vertical and horizontal forces.

"External" work has also been applied to gait analysis by Gersten, et al (15), Fukunaga, et al (14), Keneko, et al (22), Matsuo, et al (25), and by others.

The concept of "external" work has been applied to other activities. Fletcher and Lewis (13) used cine-photography to evaluate pole vaulting. They found the kinetic energy during the run-up to be proportional to the potential energy at the peak of the vault. However, Hay (20), as a result of the introduction of the fiberglass pole, found the rates of pole-bending and pole-straightening to be the predominate factors in pole vaulting performance. Gray, et al (18) used changes in the potential energy of the body's center of gravity to develop a method for estimating the power generated by leg muscles in performing a vertical jump.

The value of "external" work in these studies was that it provided the investigator with a relatively quick and easy method for determining trends and patterns in an activity. From these patterns, a researcher could then decide upon specific areas for further, more detailed, analysis.

Cavagna and co-workers (3,6) also investigated "internal" work using the method described by Fenn (11). The changes in energy of body segments were determined relative to the center of mass of the body for walking and running. They obtained efficiency values similar to Fenn (11) (0.175 to 0.225 kcal/kg/min for speeds of 11 to 20 Km/hr) for running.

Ellis and Hubbard (10) divided work done by the body system into two parts: 1) muscle forces that result in the displacement of the body, or body parts, is work done on the body system, increasing the internal energy of the system, and 2) muscle forces that result in the displacement of the surroundings is work done on the surroundings. This definition parallels the majority of the literature, in which external work is defined as work done by the body on an external mass, such as pushing or pulling a load, or lifting a weight (Winter (40)). Internal work is defined by Winter as a change in segmental energy relative to a fixed reference frame.

The above definitions differ from "external" work, which Cavagna, et al (3) defined as the work necessary to displace the center of gravity of the body and "internal" work, which is defined using displacements relative to the body's center of gravity rather than to a fixed frame of reference. These earlier definitions of "internal" and "external" work have rarely been used in the past decade.

Norman, et al proposed to use what they termed pseudowork; which is the summing of the absolute value of the change in energy of each component of a segments energy:

$$W_n = \sum_{k=1}^{m} \sum_{i=1}^{n} \left(|\Delta TKE_i| + |\Delta RKE_i| + |\Delta PE_i| \right) \qquad (12)$$

where: m - number of time increments.

n - number of body segments.

i - i^{th} body segment.

k - k^{th} time increment.

TKE - translational kinetic energy.

RKE - rotational kinetic energy.

PE - potential energy.

Δ denotes the change in the respective energy over the time increment, k.

W_n - work done, not allowing energy transfer within a segment.

They hypothesized that the subject with the lowest pseudowork (normalized by the metabolic energy expended) would be the most efficient. However, this method results in an uncharacteristically high value for the calculation of mechanical work (29). It is also questionable as to what this method is really measuring.

Winter (40) proposed calculating total mechanical work during an event as:

$$(13) \qquad W_{wb} = \sum_{k=1}^{m} \left| \sum_{i=1}^{n} \Delta E_i \right|$$

where: i,k,m,n are defined previously.

$\Delta E_i = \Delta TKE_i + \Delta RKE_i + \Delta PE_i$ (change in segmental energy of the i^{th} segment over the k^{th} time increment).

W_{wb}= work done allowing the transfer of energy within a segment and between segments.

Using this method, Winter improved on the method of Norman et al (28) by allowing the exchange of potential and kinetic energy within a segment and the exchange of energy between segments. It should be noted that this method does not allow negative work done at one point in time to cancel out positive work done at a different point in time.

Pierrynowski, et al (29) were interested in determining the work transferred between segments. Work is done on a segment by muscles connecting it with adjacent segments and by the joint reaction forces between segments. Thus, energy can be transferred from one adjacent segment to another, either by active contraction of muscle or by work done by the joint reaction forces. In an attempt to better understand the transfer of energy within the body Pierrynowski, et al defined three types of energy transfer within the body. T_w , the total transfer of energy within segments, was the change in energy form between potential energy, translational kinetic energy, and rotational kinetic energy. T_w is defined below:

$$(14) \qquad T_w = \sum_{k=1}^{m} \sum_{i=1}^{n} [(|\Delta TKE_i| + |\Delta RKE_i| + |\Delta PE_i|) - |\Delta E_i|]$$

T_b is the total transfer of energy between all body segments and is defined as:

$$(15) \qquad T_b = \sum_{k=1}^{m} [\sum_{i=1}^{n} |\Delta E_i| - | \sum_{i=1}^{n} \Delta E_i |]$$

T_{wb} is the total energy transferred within and between body segments for a given event, defined as the sum of T_w and T_b:

$$(16) \qquad T_{wb} = T_w + T_b$$

The use of the above three definitions for determining the work transferred between segments is questionable. The purpose for determining the energy transfer within segments, T_w, is not clear. T_w provides a sum of the energy transferred within the segments for an event, but provides no information on the physical forces causing the change in energy. The amount of energy transferred between segments (T_b) determines the net sum of the energy transferred between all segments of the body for a given event, but again, its usefulness is questionable. T_b does not determine what portion of energy is transferred between any two adjacent segments and it does not separate the portion of the energy transferred due to work done by the joint muscle moment from that due to the work done by the joint reaction forces.

Pierrynowski, et al (29) compared three methods for calculating total mechanical work; two methods by Norman, et al (28) and Winter (40), and an additional method defined as:

$$(17) \qquad W_w = \sum_{k=1}^{m} \sum_{i=1}^{n} |\Delta E_i|$$

where W_w is the work done, allowing energy to be transferred only within a segment but not between segments. These three methods were compared for treadmill walking.

Considering the definitions, it is easy to show that:

$$(18) \qquad W_n = T_w + W_w$$

and

$$(19) \qquad W_w = T_b + W_{wb}$$

Since T_b, T_w, and W_{wb} are always positive, then W_n will always be greater than W_w, which will always be greater than W_{wb}.

Williams and Cavanagh (37) expanded on the work of the three previous researchers. They argued that the definition of W_{wb} by Winter (40) allowed segments that are not physically in contact with each other to (mathematically) transfer energy to each other. For instance, if the left foot increased its total segmental energy over an increment of time and the right hand decreased its total segmental energy while all other segments remained unchanged then, by Winter's method, the energy of the foot could be (mathematically) transferred to the hand. To improve upon the previous works, Williams and Cavanagh developed two additional algorithms. They claimed that the first algorithm allowed energy to be transferred only between adjacent segments. The second allowed the transfer of energy within a limb but not across the trunk.

These algorithms were not expressed in equation form, but were expressed only in the form of computer algorithms (Williams (36) and Williams and Cavanagh (37)). Investigation of these algorithms by this writer could not determine any succinct method for expressing them in equation form. However, the adjacent segment algorithm published by Williams and Cavanagh (37) is directionally dependent. That is, summing from the distal segment towards the proximal segment can, under certain conditions, result in a different answer than if summed from the proximal segment towards the distal segment.

The problem with the limb transfer algorithm is that the same argument Williams and Cavanagh used against Winter (40) can be used against it. That is, positive work done on the foot segment could transfer energy (mathematically) to negative work done on the thigh, despite the fact that the two are not physically adjacent. However, with the limb transfer algorithm, energy could not be transferred across the trunk to other body segments.

Shorten, et al (32) investigated several energy transfer constraints for treadmill running at various speeds. In addition to the previously discussed methods of W_n, W_w, and W_{wb}, Shorten, et al introduced $W_{w\ell}$, which permited energy transfer within segments and between segments of the same limb. Unfortunately, they did not explicitly define $W_{w\ell}$. It was not clear whether they used the algorithm of Williams (36) or if a different method was utilized. Their results were similar to Pierrynowski, et al (29). W_n had the greatest value, followed by W_w, $W_{w\ell}$, and W_{wb}, respectively. For all the data presented, $W_{w\ell}$ was always greater than W_{wb}, but less than W_w.

Shorten, et al emphasized that their method, as well as all other energy methods, related only to changes in energy and that they were not necessarily indicative of work done by the muscles of the body. They also questioned the accuracy of energy methods since the selection of transfer constraints was not based on any knowledge of muscle contraction patterns. They further stated that, with the current energy models, it was not possible to make any definitive statements regarding mechanical efficiency.

2.3 Calculation of Mechanical Work from Kinetic Data

Elftman (7-9) wrote a thorough series of papers regarding the analysis of muscle work and muscle efficiency in human gait. Elftman (7) determined the forces and moments acting on the leg during walking. He was one of the first human motion researchers to apply kinetic data toward the investigation of mechanical work. Elftman calculated the mechanical power generated at the joints (ankle, knee, hip) by the joint reaction forces and by the joint muscle moments. He compared the rate of work done by the joint muscle moments of the leg to the rate of energy change of each segment and also discussed the role of muscle work in causing the segmental energy changes.

Elftman (8) investigated the work done by muscles that cross more than one joint. For example, muscles such as the hamstrings or quadriceps have components that cross more than one joint, extending from the pelvis to the shank, crossing both the hip and knee joint. This arrangement allows these muscles to do work on both the thigh and the shank. Elftman concluded that, under certain conditions, the multi-joint muscles can be more efficient than single joint muscles.

Elftman (9) applied his methodology to running using the data from Fenn (12). A bilateral analysis of the power generated by the muscles moments of the body's major joints (ankle, knee, hip, elbow, shoulder) was performed. He summed the rate of work done by all muscles at these joints to determine the rate of work done by "one joint muscles" for the entire body. Negative and positive work were treated separately, essentially summing the absolute values of the rate of work done. He further investigated the role of muscles crossing two joints, and again stressed the efficiency of two joint muscles.

Elftman (9) made the following statement: "In evaluating the work done by muscles on the basis of changes in kinetic and potential energy, some difficulty is encountered in allowing for the possibility that the increase in energy of one part of the body may be derived from decrease of energy in another part, instead of coming from muscular contraction. This difficulty can be eliminated if the muscle forces can be determined and the rates at which they work computed directly." (p. 672).

Quanbury, Winter, and Reimer (30) studied power flow to the shank from the power generated by the knee joint reaction forces and the knee muscle moment during the swing phase in walking. They compared the power generated on the shank from the knee forces and moments to the change in the total shank energy over time (termed instantaneous power). They showed, analytically, that power flow and instantaneous power are mathematically equivalent.

Winter, Quanbury, and Reimer (38) expanded their previous work by looking at both the knee and hip joint from toe-off to heel contact. The causes of energy changes and power flow were discussed regarding the rate of work done by the muscle moment, joint reaction forces, and gravity. In a later study, Winter and Robertson (39) expanded the previous study to include the ankle joint.

Robertson and Winter (31) analysed the above concepts of power flow and instantaneous power in walking. They improved on the previous work by including stance phase in their analysis. Close agreement was found between the power flow into each segment (foot, shank, thigh) and the instantaneous power of the segments. The only discrepancy was at the foot during heel contact and late push-off. Winter (41) examined power generated by the muscle moments at the ankle, knee, and hip joints in jogging.

Cappozzo, et al (1) analysed walking and calculated the total mechanical work done at the lower limb joints (ankle, knee, and hip), bilaterally. They compared the work done by the lower limb joints to the total energy changes of a seven segment model (three segments for each leg plus the head-arms-trunk (H-A-T) modeled as the seventh segment). The differences between the sum of the work done by the joints and the sum of the work done by the change in energy of each segment was small, except for a sharp discrepancy at heel impact.

It should be pointed out that Cappozzo, et al considered the sum of the work done by the change in segmental energy to be more reliable than summing joint work. They reasoned that segmental energy calculations had less potential for error since only one differentiation of the data was needed; whereas, with the joint work method, two differentiations were necessary to obtain the acceleration data needed for calculating the joint moments.

Martin and Siler (24) compared the transfer of energy, using the methods described by Pierrynowski, et al (29), to the work transferred to each segment from the joint reaction forces and joint muscle moments. This analysis was done for a kicking motion. They found that the sum total of the energy transfer (T_{wb}, as denoted by Pierrynowski, et al) to be nearly the same as the transfer of energy due to the work done by the joint reaction forces and moments. However the rate of the energy transfer differred markedly between the two methods. Martin and Siler concluded that the kinetic analysis was a more appropriate method for calculating the energy transferred between segments since it described the mechanisms of motion, whereas the energy analysis used the motion history without any knowledge of the mechanisms causing that motion.

Hubley and Wells (21) used a work-energy approach to analyze vertical jump performance. They normalized the absolute value of the work done at each joint (ankle, knee, and hip, bilaterally) by the sum of the total work done at all three joints. This ratio allowed a comparison between subjects for the relative amount of work done at a given joint. They determined the knee contributed the majority of the work done in vertical jumping. However, they pointed out that there were large variations in individual patterns. They suggested that further study of this method of normalization could have major implications on training and rehabilitation programs.

CHAPTER III

ANALYTICAL METHODS

3.1 **Analytical Model**

The following assumptions were made for the model used in this thesis:

1.) All motion is in the sagittal plane.

2.) During stance phase the foot rolls without slipping, therefore no work is done by the ground reaction forces.

3.) All forces (except the ground reaction forces) are assumed to act through the joint centers.

4.) The joint centers are assumed to be located at fixed locations on each segment. These locations are defined by either the target positions on each segment or by a given location relative to the targets on each segment.

5.) All muscle effects on a joint are represented by a single muscle moment acting at that joint.

6.) Positive work done by a muscle consumes the same amount of metabolic energy as an equal amount of negative work done by that same muscle.

In a multi-segmental body, the forces and moments acting on the i^{th} segment are shown in Figure 1.

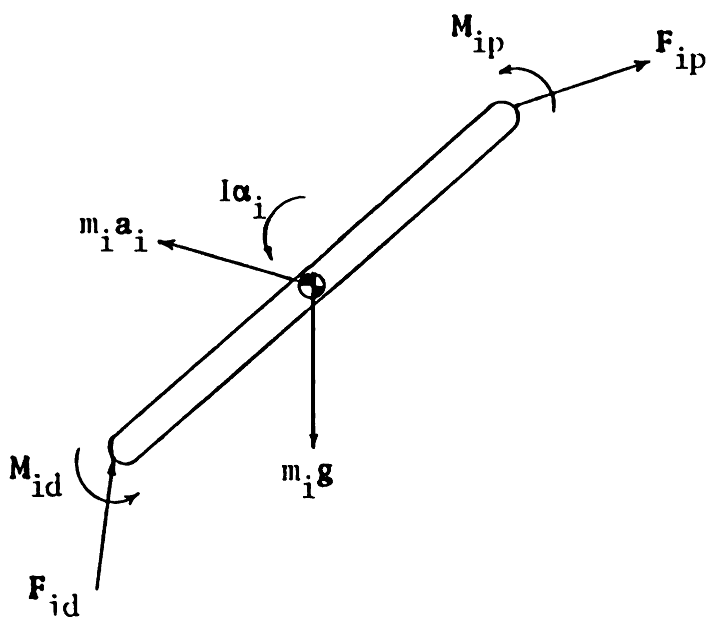


Figure 1

Forces and moments acting on the i^{th} body segment.

Where the following notation applies to Figure 1:

F are the joint reaction forces.

M are the muscle moments.

i denotes the i^{th} segment.

d denotes the distal end of the segment.

p denotes the proximal end of the segment.

m_i is the mass of segment "i".

$\mathbf{a}_i$ is the acceleration of segment "i".

α_i is the angular acceleration of segment "i".

"I" is the moment of inertia of the segment about an axis perpendicular to the sagittal plane.

g is the acceleration of the segment due to gravity.

All of the above vectors were defined with respect to a fixed reference frame.

The distal and proximal forces and moments were calculated for each segment using the procedure described by Markus (23). Elftman (7) also provides a thorough description for calculating the forces and moments acting at each segment. For the foot, the distal forces (ground reaction forces) were measured, for the stance phase of gait, using a force plate. During swing phase, the distal foot forces were zero. From cinematic film data, the linear and angular accelerations of the foot center of mass were known. Thus, from dynamics, the proximal (ankle) joint reaction forces and the ankle joint muscle moment could be determined.

For the shank, the distal shank forces and moments were equal and opposite to the proximal foot forces and moments. Since the linear and angular accelerations of the shank center of mass were known from film data, the proximal shank forces and moments could be determined from dynamics. The same procedure was used for the thigh segment.

For the upper limb, the distal forces on the hand segment were zero. Thus by knowing the linear and angular accelerations of the center of mass of the hand, the proximal hand forces and moments were determined. The distal forces of the forearm were equal and opposite to the proximal forces of the hand segment, thus, the proximal forearm forces could be determined since the linear and angular accelerations of the forearm center of mass were known from cinematic data. Continuing this process, the distal and proximal forces acting on each segment were determined. The forces and moments acting on the trunk were equal and opposite to the proximal forces acting on the thigh, upper arm, and head-neck segments.

The work (ΔW_i) done on the segment shown in Figure 1, for a given increment of time, is as follows:

$$(20) \quad \Delta W_i = F_{id} \cdot \Delta S_{id} + F_{ip} \cdot \Delta S_{ip} + (M_{id} + M_{ip}) \cdot \Delta \theta_i + m_i g \cdot \Delta S_i$$

where: ΔS_i is the incremental displacement of the i^{th} segment's center of mass.

ΔS_{id} and ΔS_{ip} are the incremental position changes of the distal and proximal ends of the i^{th} segment.

$\Delta \theta_i$ is the incremental angular position change of the segment.

From rigid body mechanics, the work done on a segment is equal to the change in kinetic energy of that segment. From Figure 1, consider the work done on the proximal portion of the i^{th} segment, ΔW_{ip}:

$$(21) \quad \Delta W_{ip} = F_{ip} \cdot \Delta S_{ip} + M_{ip} \cdot \Delta \theta_i$$

However, ΔS_{ip} can be expressed as:

$$(22) \quad \Delta S_{ip} = \Delta S_i + \Delta \theta_i X \, r_{ip}$$

where: r_{ip} is a vector from the center of mass of the segment to the proximal end of the segment.

ΔS_i and ΔS_{ip} are as previously defined.

Thus, equation (21) can be rewritten as:

$$(23) \quad \Delta W_{ip} = F_{ip} \cdot [\Delta S_i + (\Delta \theta_i X \, r_{ip})] + M_{ip} \cdot \Delta \theta_i$$

Using the vector identity $\mathbf{A}\cdot(\mathbf{B} \times \mathbf{C}) = \mathbf{B}\cdot(\mathbf{C} \times \mathbf{A})$ equation (23) can be written as:

$$(24) \qquad \Delta W_{ip} = \mathbf{F}_{ip}\cdot \Delta \mathbf{S}_i + [(\mathbf{r}_{ip} \times \mathbf{F}_{ip}) + \mathbf{M}_{ip}]\cdot\Delta\boldsymbol{\theta}_i$$

Similarly, the work done on the distal segment is:

$$(25) \qquad \Delta W_{id} = \mathbf{F}_{id}\cdot\Delta \mathbf{S}_{id} + \mathbf{M}_{id}\cdot\Delta\boldsymbol{\theta}_i$$

As with $\Delta \mathbf{S}_{ip}$, $\Delta \mathbf{S}_{id}$ can be rewritten in terms of the segment's change in its center of mass position ($\Delta \mathbf{S}_i$) and the change in the angular position of the segment ($\Delta\boldsymbol{\theta}_i$):

$$(26) \qquad \Delta \mathbf{S}_{id} = \Delta \mathbf{S}_i + \Delta\boldsymbol{\theta}_i \times \mathbf{r}_{id}$$

where $\mathbf{r}_{id}$ is the vector from the segment's center of mass to the distal joint of the segment.

Thus the work done on the distal end of the segment can be written as:

$$(27) \qquad \Delta W_{id} = \mathbf{F}_{id}\cdot \Delta \mathbf{S}_i + [(\mathbf{r}_{id} \times \mathbf{F}) + \mathbf{M}_{id}]\cdot\Delta\boldsymbol{\theta}_i$$

The total work done on the segment is:

$$(28) \qquad \Delta W_i = \Delta W_{ip} + \Delta W_{id} + m_i\mathbf{g}\cdot\Delta \mathbf{S}_i$$

or:

$$(29)\quad \Delta W_i = (\mathbf{F}_{id} + \mathbf{F}_{ip} + m_i\mathbf{g})\cdot\Delta\mathbf{S}_i + (\mathbf{M}_{id} + \mathbf{M}_{ip} + \mathbf{r}_{id} \times \mathbf{F}_{id} + \mathbf{r}_{ip} \times \mathbf{F}_{ip})\cdot\Delta\boldsymbol{\theta}_i$$

The portion in brackets in the first part of equation (29) is the sum of the forces acting on the center of mass of a segment dotted with the distance through which these forces travel. This is equivalent to the change in the translational kinetic energy:

$$(30)\quad (\mathbf{F}_{id} + \mathbf{F}_{ip} + m_i\mathbf{g})\cdot\Delta\mathbf{S}_i = m_i\mathbf{a}_i\cdot\Delta\mathbf{S}_i$$

$$m_i\mathbf{a}_i\cdot\Delta\mathbf{S}_i = m_i[(\mathbf{v}_{i2}-\mathbf{v}_{i1})/\Delta t]\cdot[(\mathbf{v}_{i2}+\mathbf{v}_{i1})/2]\Delta t$$

$$= 1/2\ m_i(v_{i2}^2 - v_{i1}^2)$$

Where $\mathbf{v}_{i1}$ and $\mathbf{v}_{i2}$ are the velocities of the i^{th} segment's center of mass at the beginning and end of the time interval, respectively. Note that the accelerations and forces are assumed to be constant over the time interval.

Similarly, the second part of equation (29) is the sum of the moments about the center of mass, dotted with the change in angular position of the segment. This is equivalent to the change in the rotational kinetic energy:

$$(31)\quad (\mathbf{M}_{id} + \mathbf{M}_{ip} + \mathbf{r}_{id} \times \mathbf{F}_{id} + \mathbf{r}_{ip} \times \mathbf{F}_{ip})\cdot\Delta\boldsymbol{\theta}_i = I_i\boldsymbol{\alpha}_i\cdot\Delta\boldsymbol{\theta}_i$$

$$= I_i[(\boldsymbol{\omega}_{i2} - \boldsymbol{\omega}_{i1})/\Delta t]\cdot[(\boldsymbol{\omega}_{i2} + \boldsymbol{\omega}_{i1})/2]\Delta t$$

$$= 1/2\ I_i(\omega_{i2}^2 - \omega_{i1}^2)$$

Where ω_{i1} and ω_{i2} are the angular velocities of the i^{th} segment at the beginning and end of the time interval, respectively.

Thus the total work done on the segment can be written as:

$$(32) \quad \Delta W_i = 1/2\ m_i(v_{i2}^2 - v_{i1}^2) + 1/2\ I_i(\omega_{i2}^2 - \omega_{i1}^2)$$

In motion analysis, time is a more convenient variable over which to sum than variables such as distance or angular position. With this in mind, the variable of summation will be changed to time and the following definitions will be made:

$$\Delta W_{Fdi} = \mathbf{F}_{id} \cdot \Delta \mathbf{S}_{id} = \mathbf{F}_{id} \cdot (\Delta \mathbf{S}_{id}/\Delta t)\Delta t = \mathbf{F}_{id} \cdot \mathbf{v}_{id}\Delta t$$

$$\Delta W_{Fpi} = \mathbf{F}_{ip} \cdot \Delta \mathbf{S}_{ip} = \mathbf{F}_{ip} \cdot \mathbf{v}_{ip}\Delta t$$

$$\Delta W_{Mdi} = \mathbf{M}_{id} \cdot \Delta \boldsymbol{\theta}_i = \mathbf{M}_{id} \cdot \boldsymbol{\omega}_i\ \Delta t$$

$$\Delta W_{Mpi} = \mathbf{M}_{ip} \cdot \Delta \boldsymbol{\theta}_i = \mathbf{M}_{ip} \cdot \boldsymbol{\omega}_i\ \Delta t$$

where ΔW_{Fdi} and ΔW_{Fpi} are the work done by the distal and proximal joint reaction forces and ΔW_{Mdi} and ΔW_{Mpi} represent the work done by the distal and proximal muscle moments acting on segment "i". Note that $\mathbf{v}_{id}$, $\mathbf{v}_{ip}$, and $\boldsymbol{\omega}_i$ are the average velocities and angular velocities, respectively, over the time interval.

3.2 **Joint Muscle Moment Work**

In order to study human efficiency, the work done by the muscles of the body must be determined. The following analysis determines the work done by a joint muscle moment, which does not necessarily account for the work done by all the muscles acting at a joint. The work performed by antagonistic muscle contractions or by isometric contractions is not included.

The joint reaction forces between adjacent segments (shown in Figure 2) are equal and opposite and act through very nearly the the same distance. If the joints were in pure rotation, the net work done by the joint reaction forces would be exactly zero. However, there is some compliance within each joint and thus these forces do work. But this work is small relative to the work done by the joint muscle moment, thus the net work done by the joint reaction forces can be assumed negligible.

The work done by the joint muscle moment at joint "j" is equal to the muscle moment at the joint dotted with the change in angular position of the joint. Using time as the variable of summation, the work done by a joint muscle moment (ΔW_{Mj}) is:

$$(33) \qquad \Delta W_{Mj} = \mathbf{M}_j \cdot \boldsymbol{\omega}_j \ \Delta t$$

where $\mathbf{M}_j$ is the moment acting at the joint and $\boldsymbol{\omega}_j$ is the average angular velocity of the joint over the time increment, Δt. The j^{th} joint is defined as shown in Figure 2. Joint "j" is between distal segment "i" and proximal segment "i+1". Thus, relative to the segmental data, the joint moment is equal to the proximal moment acting on segment "i" and the joint angular velocity is equal to the difference in the angular velocities between segment "i" and segment "i+1".

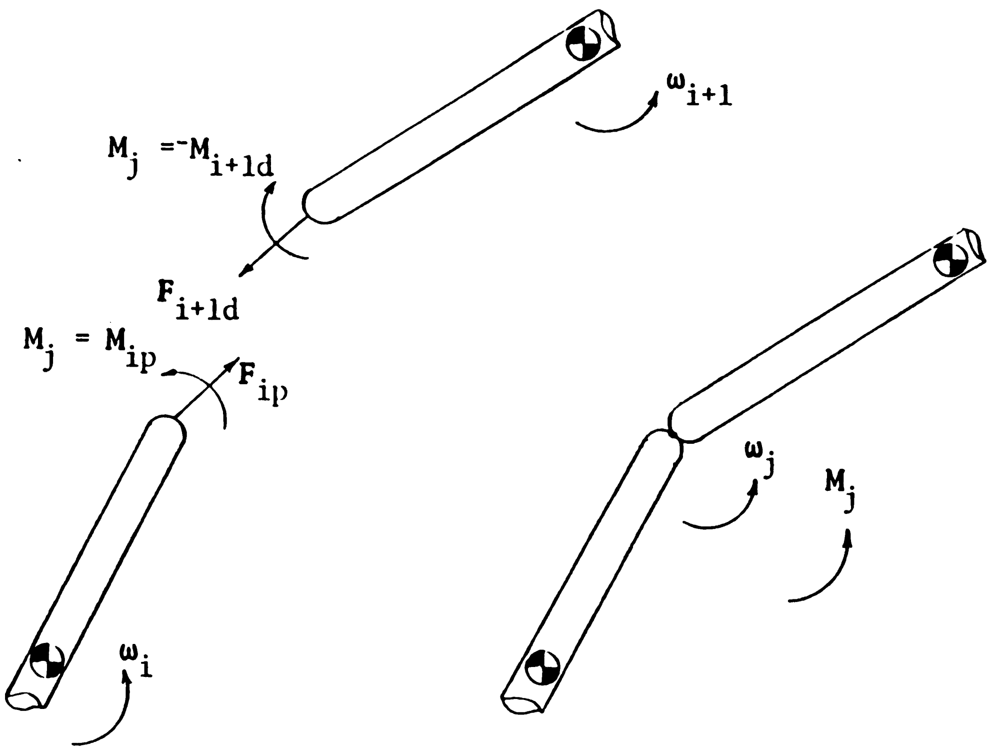


Figure 2

Relationship between the joint muscle moment and the joint angular velocity to segmental muscle moments and segmental angular velocity.

The following notation applies to Figure 2:

M_{ip} - proximal muscle moment of segment "i".

M_{i+1d}- distal muscle moment of segment "i+1".

ω_i and ω_{i+1} are the angular velocities of the respective segments.

$M_j = M_{ip} = - M_{i+1d}$

$\omega_j = \omega_i - \omega_{i+1}$

3.3 Summing Muscle Moment Work

The simplest model for summing muscle moment work would be to sum the work done by each joint:

$$(34) \qquad \sum_{j=1}^{q} \Delta W_{Mj}$$

where q is the total number of joints in the model. However, this would be assuming perfect efficiency. Positive work done by one joint could be recovered by negative work done at any other joint, without any losses in work efficiency.

It was assumed that the muscle moment about each joint was caused by "one-joint" muscles as defined by Elftman (8). That is, the effect of "two-joint" muscles, such as the hamstrings (which cross two joints, the hip and the knee, and are thus capable of doing work at both joints), will not be considered. Thus, by definition, energy can only be transferred to segments that are immediately adjacent to each other by work done by the joint reaction forces and/or the joint muscle moments. Hence, the work done by a series of joints over any given instant in time is the sum of the absolute value of the work done at each joint:

$$(35) \qquad W_k = \sum_{j=1}^{q} |\Delta W_{Mj}| = \sum_{j=1}^{q} |M_j \cdot \omega_j| \, \Delta t$$

where: W_k = the work done during the k^{th} time interval.

q = number of joints in the model.

Hence positive work done at one joint is not cancelled out by negative work done at a different joint. Equation (35) ignores oscillatory motions during the time interval, and therefore requires that the time interval be small enough so that the work calculated for the time period is representative of the actual work done by the muscle moments involved.

If the total work done by the muscles of the body is desired for a given event, then:

$$(36) \qquad W_{total} = \sum_{k=1}^{m} \sum_{j=1}^{q} |W_{Mj}| = \sum_{k=1}^{m} \sum_{j=1}^{q} |\mathbf{M}_j \cdot \omega_j| \, \Delta t$$

where W_{total} is the work done by all the muscle moments of the body for the entire event.

CHAPTER IV

EXPERIMENTAL METHODS

The experimental methods were divided into four sections: equipment, subject, data collection, and data processing.

4.1 Equipment

Two LOCAM 16mm cine-cameras operating at 100 frames per second were used to record position data. The cameras were positioned so that anterolateral and posterolateral views of the subject within the force plate area were filmed. The camera positions were such that all targets on the left side of the subject's body were visible in both camera views during the stance phase of the subject on the force plate. The cameras were connected to a single switch, allowing both cameras to be triggered at approximately the same time. In order to synchronize the film data each camera's field of view contained a timing light box. The timing lights were synchronized and accurate to 1/1000 seconds. The timing lights allowed the processed film to be time-matched after digitization.

A calibration structure, consisting of 12 targets of known position, was placed in the view field of the cameras. The calibration structure provided a known coordinate system to define the space of the viewing area. Using the method of direct linear transformation (Walton (35)) the appropriate transformation matrices were determined; thus the three dimensional coordinates of any target within the field of view of both cameras could be calculated. The calibration structure was removed to allow data to be filmed of the subject standing and running.

Ground reaction forces were measured using an AMTI three dimensional strain gage force platform (model OR6-3 Advanced Mechanical Technology, 141 California Street, Newton, MA 02158). The strain gage voltage output was converted to digital data with an A to D converter sampling the output at the rate of 1000 samples per second. The digital data was calibrated and processed such that force and moment data (measured in Newtons and Newton-meters, respectively) were recorded for the three principle directions (X,Y,Z) on an 8 inch floppy disk. The data was transferred to a Prime mainframe computer in the Case Center for Computer-Aided Design. The orientation of the force plate coordinate system is shown in Figure 3.

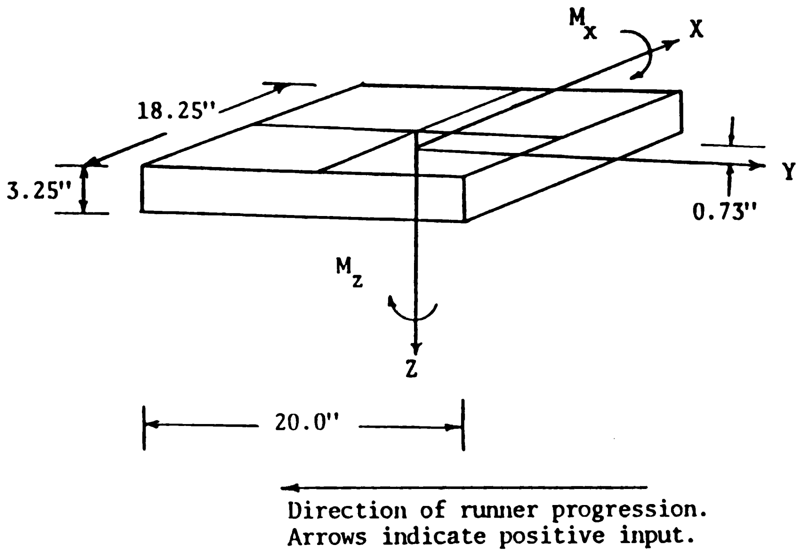


Figure 3

Force plate coordinate system

4.2 Subject

The subject of this study was a 30 year old male weighing 64 Kg with a running experience of 13 years at 70 miles per week. Fourteen 1/2 inch diameter cotton pom poms were used as targets to define eight body segments. The target positions are shown in Figure 4. Symmetry was not assumed in this study. Table I gives the target number, the anatomical landmark over which the target was placed, and the body segment the targets defined.

The appropriate anthropometric measurements were recorded so that segment mass, center of mass, and moment of inertia could be determined. NASA Reference Publication 1024 (27) was used as the anthropometric reference for this study.

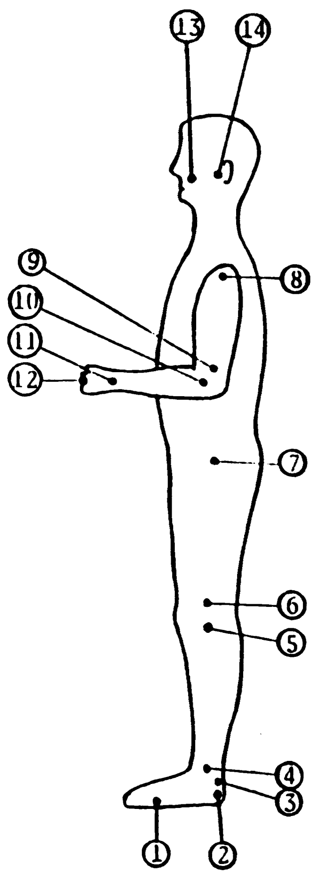


Figure 4

Target locations on the subject.

Table 1
Target position and segment definition

Target	Landmark (on left side of body)	Segment
1	5th metatarsal tuberosity	
2	Upper portion of calcaneus	Foot
3	Lower portion of calcaneus	
4	Lateral malleolus	Shank
5	Fibular head	
6	Lateral femoral condyle	Thigh
7	Greater trochanter	Trunk
8	Greater tuberosity of humerus	Upper arm
9	Lateral condyle of humerus	
10	Head of radius	Forearm
11	Lunate (dorsal aspect)	Hand
12	Head of 3rd metacarpal	
13	Ant. portion of zygomatic arch	Head
14	Post. portion of zygomatic arch	

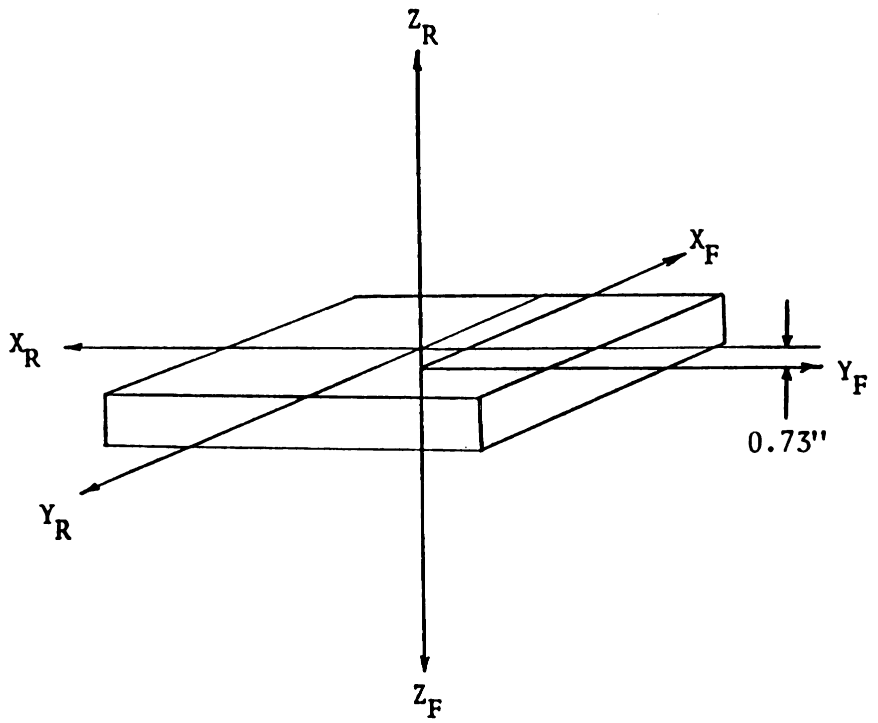
4.3 Data Collection

Three trials were filmed of the subject striking the force plate during the stance phase of running. The subject was encouraged to keep his stride natural and unforced. If the subject missed the force plate or if he felt his stride was forced in any manner, then the trial was repeated. A subject identification board, visible in both camera views, was used to identify the subject and trial number of the run.

The film was digitized using an Altek Datatab rear projection digitizer (Altek Corporation, 2150 Industrial Parkway, Silver Spring, MD 20904). The calibration structure was digitized first, followed by the subject standing position. The force plate was also digitized in order to define the force plate position with respect to the calibration coordinate system. The film from the three successful running trials was then digitized. Fifteen frames before heel strike and 4 frames after toe-off were digitized. Unfortunately only 4 film frames after toe-off could be digitized due to the loss of target visualization on one camera view. The digitized data was recorded on a floppy disk and transferred to the Prime mainframe in the Case Center for Computer-Aided Design.

4.4 Data Processing

During the digitizing process it was noted that the timing light for camera one (the anterolateral view) was not consistently synchronized with the primary timing light. The variability of the frame time for camera one was calculated for several portions of the film and was found to vary by +/-0.00026 seconds per frame. This indicated that the timing light was consistent, in spite of the loss of synchronization. The data for each running trial was time-matched by assuming heel contact occurred simultaneously in both camera views. The initial and final times for camera one were adjusted relative to the heel contact time. The three dimensional position for each target was then determined from the time-matched data using a series of computer programs. The data was filtered through a two pass Butterworth filter with a cutoff frequency of 8 Hz. The position data was run through a transformation program so that the center of the force plate was the origin of the coordinate system. Figure 5 shows the relationship between the force plate coordinate system and the final coordinate system used for data analysis. The number of data points were reduced so that only five time intervals (1/100 seconds each) before heel strike and four time intervals after toe-off were analyzed. The purpose for this was to reduce the effect of the filter which is reported to attenuate target accelerations during swing phase (31).



(X_F, Y_F, Z_F) = Force plate coordinate system.

(X_R, Y_R, Z_R) = Final coordinate system for data analysis.

Figure 5

Force plate coordinate system and final film data coordinate system.

The three dimensional position data was collapsed to a two dimensional plane parallel to the X_R-Z_R plane shown in Figure 5. This plane was approximately parallel with the sagittal plane of the subject during the run. The position data was then differentiated. The velocity data was obtained using a three point forward difference for the first two time intervals, a five point central difference for the remaining time intervals, except the last two intervals, where a three point backward difference was used. A similar method was used for the acceleration data, except the forward and backward differences were four point. With this method, no data was lost due to numerical differentiation.

The kinematic data was calculated for each segment using methods similar to those described by Markus (23). The kinetic data for the lower limb was obtained by time-matching the kinematic data and the force plate data. Since the force plate data was initiated by the impact of heel strike, it was assumed that the first frame of heel strike and the first force plate data sample occurred at the same instant in time. The center of pressure between the foot and force plate was determined for each time interval of kinematic data. Since data collection for the force plate was at 1000 Hz and data collection for the filmed data was at 100 Hz, every 10^{th} force plate data point was used. The center of pressure was then transformed to the two dimensional runner coordinate system. Thus, the position and magnitude of the forces acting on the foot segment were known. Simple dynamics allowed the calculation of the forces and moments acting on the ankle, knee, and hip. For the upper limb and for the head and neck, the forces at the wrist, elbow, shoulder, and neck were determined from the kinematic and inertial data. The forces and moments acting at the distal and proximal ends of each segment on the left side of the subjects body were determined for the stance phase of running.

The kinematic data allowed the calculation of the kinetic energy components for each segment. The position data was used to determine the potential energy, and the kinetic data, combined with the kinematic data, allowed the work done by the forces and moments acting on each segment to be calculated.

CHAPTER V

RESULTS AND DISCUSSION

5.1 Analytical Results and Discussion

The literature concentrates almost exclusively on the use of segmental energy changes for calculating total body work. However, it is not immediately apparent as to what these methods are physically related to. Shorten, et al (32) pointed out that the energy methods currently available do not necessarily relate to the work done by the muscles of the body. The purpose of this discussion is to ascertain the physical significance of the energy methods that have been reviewed and to relate the results of the analytical methods to the literature.

Equations (21) through (32) show the relationship between the work done on a segment to the change in the kinetic energy of that segment. If the work done by gravity on a segment is written in its potential form, it can be expressed on the energy side of the work-energy equation. Thus:

$$(37) \quad \Delta W_{Fdi} + \Delta W_{Fpi} + \Delta W_{Mdi} + \Delta W_{Mpi} = \Delta E_i = \Delta TKE_i + \Delta RKE_i + \Delta PE_i$$

The sum of the segmental change in energy can be written as:

$$(38) \quad \sum_{i=1}^{n} \Delta E_i = \sum_{i=1}^{n} \Delta W_{Fdi} + \Delta W_{Fpi} + \Delta W_{Mdi} + \Delta W_{Mpi}$$

The net work done by the joint reaction forces between two adjacent segments is assumed small compared to the work done by the joint muscle moment. Thus, equation (38) can be written as:

$$(39) \qquad \sum_{i=1}^{n} \Delta W_{Mdi} + \Delta W_{Mpi} = \sum_{i=1}^{n} (\mathbf{M}_{id} + \mathbf{M}_{ip}) \cdot \boldsymbol{\omega}_i \, \Delta t$$

The relationship between joint "j" with distal segment "i" and proximal segment "i+1" is shown in Figure 2 and equation (33). Therefore the work can be summed over the joints "j":

$$(40) \qquad \sum_{i=1}^{n} (\mathbf{M}_{id} + \mathbf{M}_{ip}) \cdot \boldsymbol{\omega}_i \, \Delta t = \sum_{j=1}^{q} \mathbf{M}_j \cdot \boldsymbol{\omega}_j \, \Delta t$$

Equation (38) can be summed over the time intervals for the event of interest to give:

$$(41) \qquad W_E = \sum_{k=1}^{m} \sum_{i=1}^{n} \Delta E_i = \sum_{k=1}^{m} \sum_{j=1}^{q} \mathbf{M}_j \cdot \boldsymbol{\omega}_j \, \Delta t = \sum_{k=1}^{m} \sum_{j=1}^{q} \Delta W_{Mj}$$

where W_E is the sum of the segmental energy changes for the entire event.

The above analysis relates the sum of the energy changes in body segments to the sum of the work done by the muscles of the body. Equation (41) represents the most idealistic transfer of work between joints that is possible. Equation (41) can be applied to determine the physical significance of some of the energy methods discussed previously.

In the method of Norman, et al (28), W_n was defined in equation (12). The problems associated with this method are immediately apparent. Disregarding the transfer of energy within a segment (translational kinetic energy to rotational kinetic energy to potential energy, or any combination of the three energy forms) does not relate to any physical behavior of the work done by the joint reaction forces or muscle moments.

In the method of Winter (40), W_{wb} is shown in equation (13). To understand its physical significance, it is rewritten here in its component form:

$$(42) \qquad W_{wb} = \sum_{k=1}^{m} \left| \sum_{i=1}^{n} \Delta W_{Fdi} + \Delta W_{Fpi} + \Delta W_{Mpi} + \Delta W_{Mdi} \right|$$

Using the same argument regarding the negligible work done by the joint reaction forces, equation (42) can be written as:

$$(43) \qquad W_{wb} = \sum_{k=1}^{m} \left| \sum_{j=1}^{q} \Delta W_{Mj} \right|$$

Thus, Winter's method allowed for the perfect transfer of work done between all body joints for a given instant in time. This method was an improvement over the simple summation of segmental work, because it did not allow positive work done during one interval of time to be cancelled out by negative work done during some other interval of time.

Pierrynowski, et al (29) defined W_w as shown by equation (17). This can be written in component form as:

$$(44) \quad W_w = \sum_{k=1}^{m} \sum_{i=1}^{n} |\Delta E_i| = \sum_{k=1}^{m} \sum_{i=1}^{n} |\Delta W_{Fdi} + \Delta W_{Fpi} + \Delta W_{Mdi} + \Delta W_{Mpi}|$$

The work done by the joint reaction forces is within the absolute value signs thus the work done by the proximal forces of one segment cannot be (mathematically) cancelled out by work done by the distal force of the adjacent segment. As a result, the previous assumption that allowed the work done by the joint reaction forces to be considered negligible is not valid for equation (44).

Summing the absolute value of the joint work is not entirely new to the literature. Elftman (9) used similar assumptions to arrive at the same basic conclusion of equation (36). Elftman summed the absolute values of the power generated at each joint, but did not express his analysis nor his conclusions in equation form. He investigated the rate of work done by one- and two-joint muscles in running. He used the same basic idea of equation (36) as a model for the least efficient use of joint muscle power. For the upper bounds of efficiency, Elftman used a model in which work could be transferred from or to any other joint in the body without loss. This model would be equivalent to equation (41), written in terms of power. The emphasis of Elftman's study was that two-joint muscles must be taken into consideration because of the great improvement in efficiency that they provide.

Hubley and Wells (21) also used the concept of summing the absolute value of the work done at each joint. However, they used this value as a method for normalizing the work done by the hip, knee, and ankle joints in a vertical jump. This ratio allowed a comparison between subjects for the work done at each of these joints.

5.2 Experimental Results and Discussion

5.2a Segmental Work

Theoretically, the work done on a segment is equal to the change in energy of that segment. In order to verify the accuracy of the data collected and the accuracy of the model, the work done on each segment by the joint reaction forces and by the joint muscle moments was compared to the change in energy of each segment. The two methods were found to be almost identical for all segments except for the foot.

The work done on the foot, calculated using both the energy method and the kinetic (work) method, is shown in Figure 6. Note the differences between the two methods during the entire stance phase; especially at heel contact and before toe-off. The energy method of calculating work shows that the work done on the foot is negative at heel contact and becomes increasingly positive between mid-stance and toe-off. The work calculated using force and moment data shows a sharp positive work increase for the work done on the foot at heel contact, followed by negative work done during mid-stance, remaining negative until toe-off. In Figure 7 the work done by the ankle joint reaction forces on the foot is compared to the work done by the ankle joint muscle moment on the foot. The work done by the ankle joint muscle moment is nearly equal in magnitude, but opposite in sign, to the work done by the ankle joint reaction forces on the foot. Thus, small errors in measuring or calculating either one of these components could explain the discrepancy.

Robertson and Winter (31) obtained results similar to Figure 6 and Figure 7. They compared the power generated from the ankle

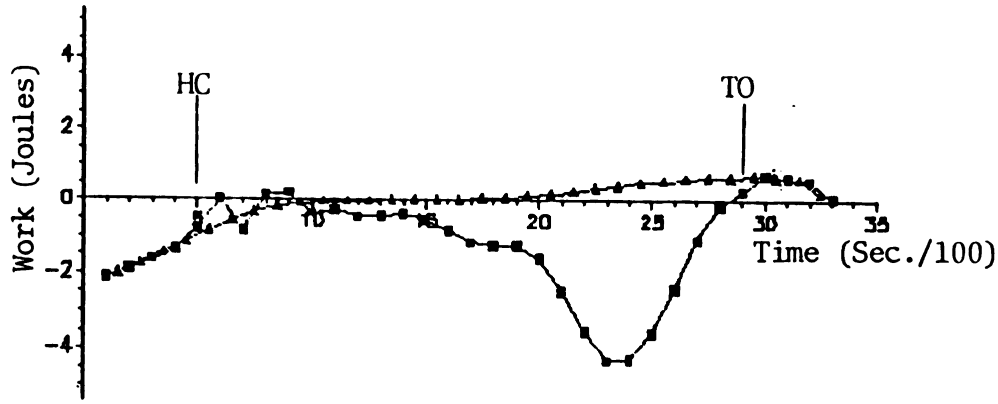


Figure 6a Run #1

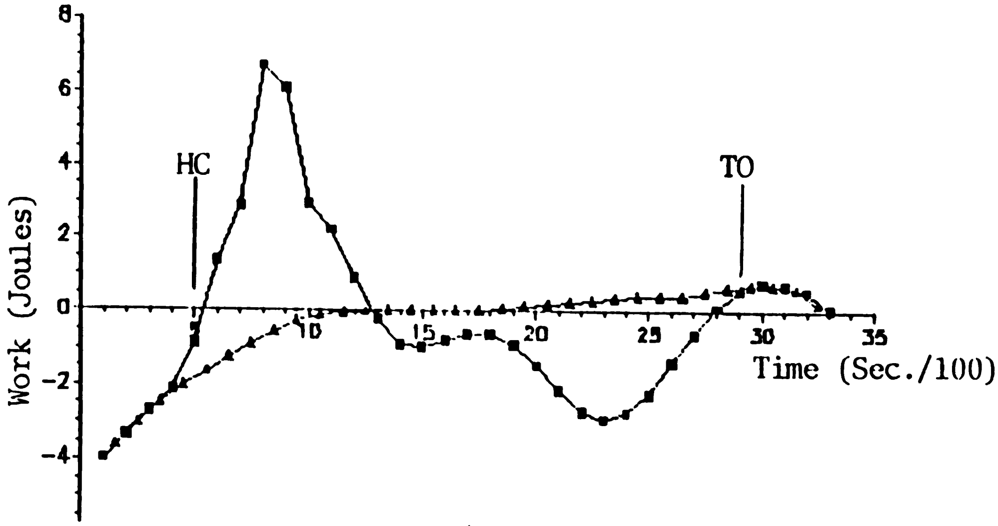


Figure 6b Run #2

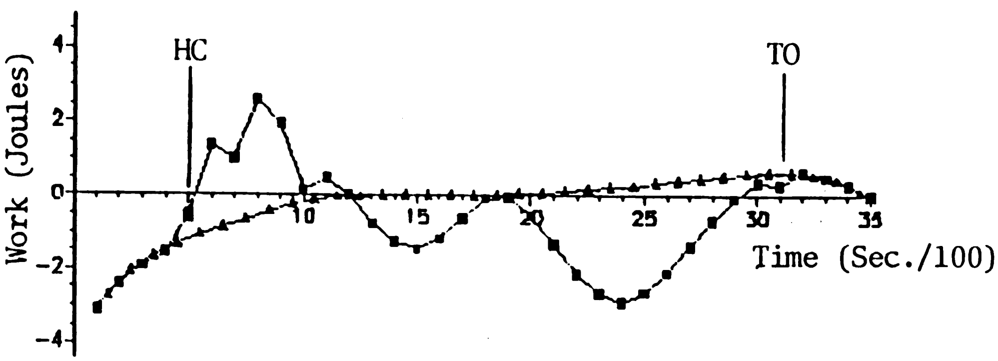


Figure 6c Run #3

Energy Method
Work Method

Figure 6 Work done on the foot segment.

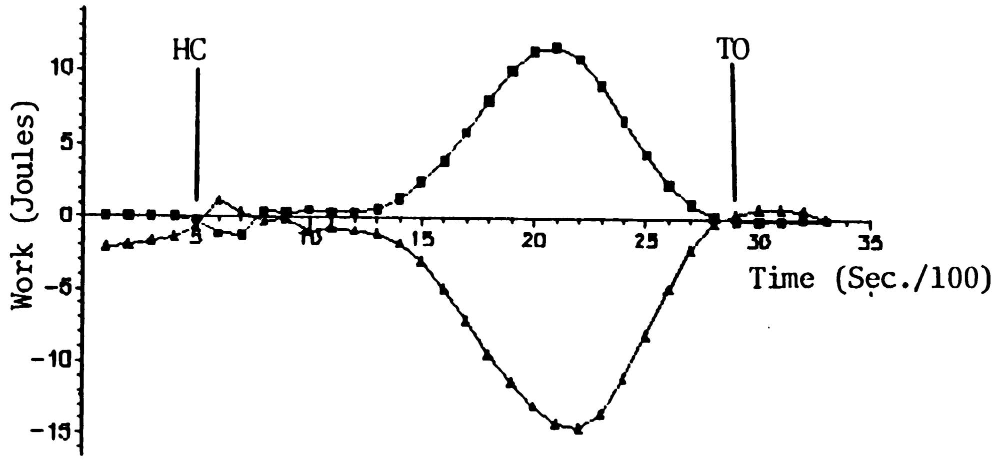


Figure 7a Run #1

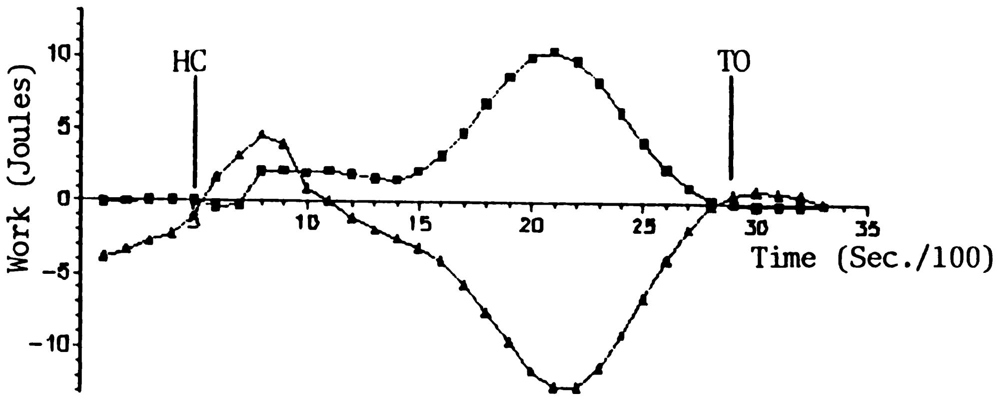


Figure 7b Run #2

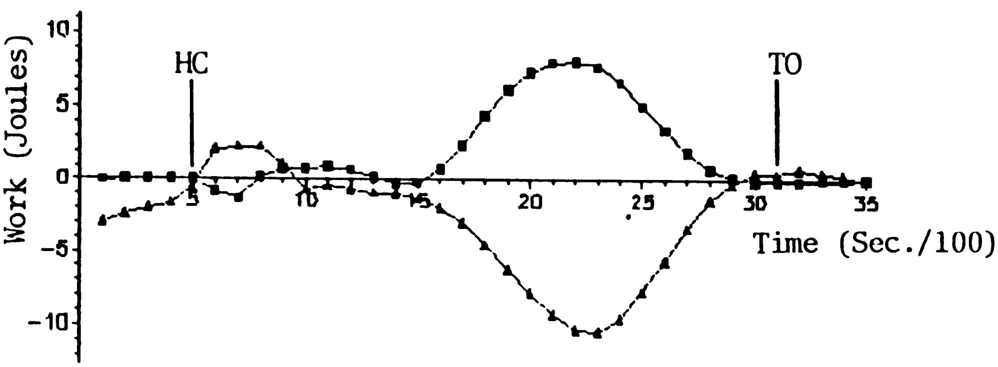


Figure 7c Run #3

Joint Force Work
Joint Moment Work

Figure 7 Work done by the ankle muscle moment compared to the work done by the ankle joint reaction forces.

joint reaction forces and muscle moment acting on the foot to the rate of change of the kinetic energy of the foot. They reported a discrepancy between the two methods for the foot at heel contact and late push-off. They proposed that changes in the ankle joint center of rotation may explain the discrepancy. The model used by Robertson and Winter and the model used in this study assumed a fixed center of rotation for the ankle joint. However, it is known that the actual center of rotation changes during stance phase. Thus, the ankle joint moment calculated for a fixed joint model would differ from that of a model which included the change in the center of rotation of the joint. Hence, the work done by the muscle moment would change accordingly. Additionally, the work done by the joint reaction force would change. Although the magnitude of the force would remain essentially the same, the force would be located at different points on the ankle joint and would travel through a different path, thus changing the amount of work done by that force.

Figures 8 through 13 are presented to show the comparison between the work done on each segment to the change in energy of each segment for the left shank, thigh, hand, forearm, upper arm, and head. The two methods were found to be almost identical, as one would expect.

The above argument concerning the joint center of rotation should apply to all segments, not just the foot. A possible reason that there is little discrepancy for the remaining segments is that any change in the distal kinetics of a segment will alter the dynamic equations so that the proximal kinetics will also change. Thus, although the work done by the distal and proximal forces would change, the total work done on a segment would remain the same. The foot, however, is constrained by the assumption that the ground reaction forces do no work. Thus, if the exact path that the ankle forces and moments travel through is not known, there will be a good chance of discrepancy between the energy method of calculating work and the kinetic method of calculating work. By this argument, the energy method of calculating segmental work is probably the more accurate of the two.

The work done on the segments of the lower limb followed a general trend: negative work was done on the foot, shank, and thigh segments as they decelerated before heel contact. The segmental work remained negative for approximately half of stance phase. Positive work was done on these segments during the latter half of stance phase and increased to a peak near toe off. Immediately after toe off, the work was found to decrease at a rapid rate, and became negative for the shank and thigh as these segments decelerated during the back swing phase of the movement. Williams and Cavanagh (37) showed similar trends for the total lower limb energy changes.

The work patterns for the segments of the upper limb were found to be almost a mirror image of that of the lower limb. Both before and after heel contact, positive work was done on the hand, forearm and upper arm segments, but in a decreasing amount. At approximately the first quarter of stance phase the work done on these segments was negative and remained negative, with the exception of Run #1 for the upper arm. After toe off the work

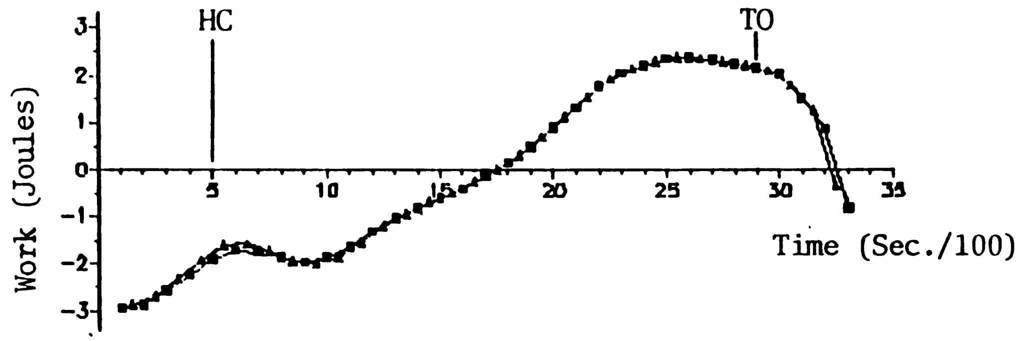


Figure 8a Run #1

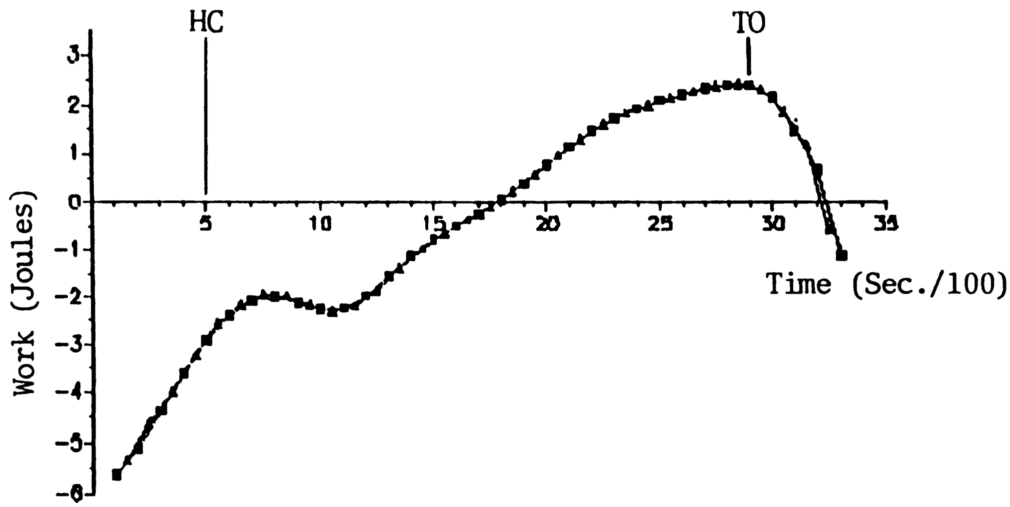


Figure 8b Run #2

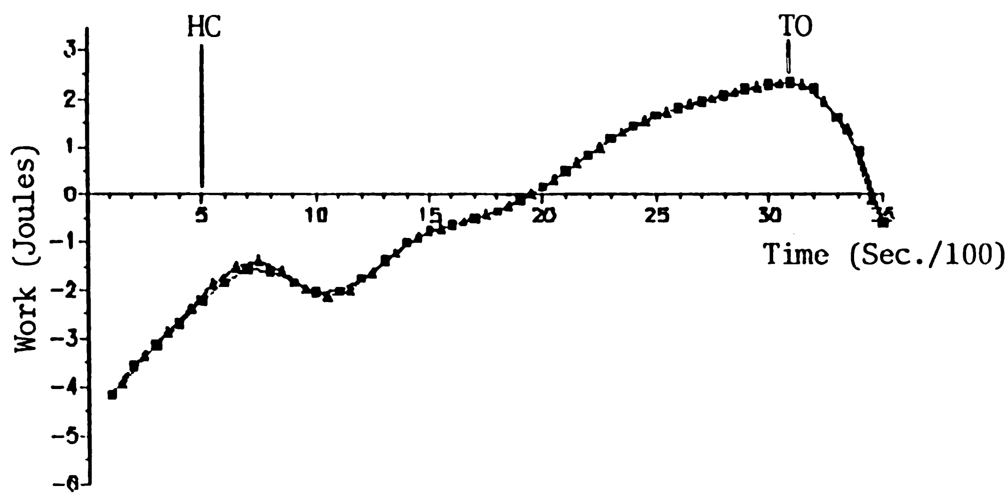


Figure 8c Run #3

Figure 8 Work done on the shank segment.

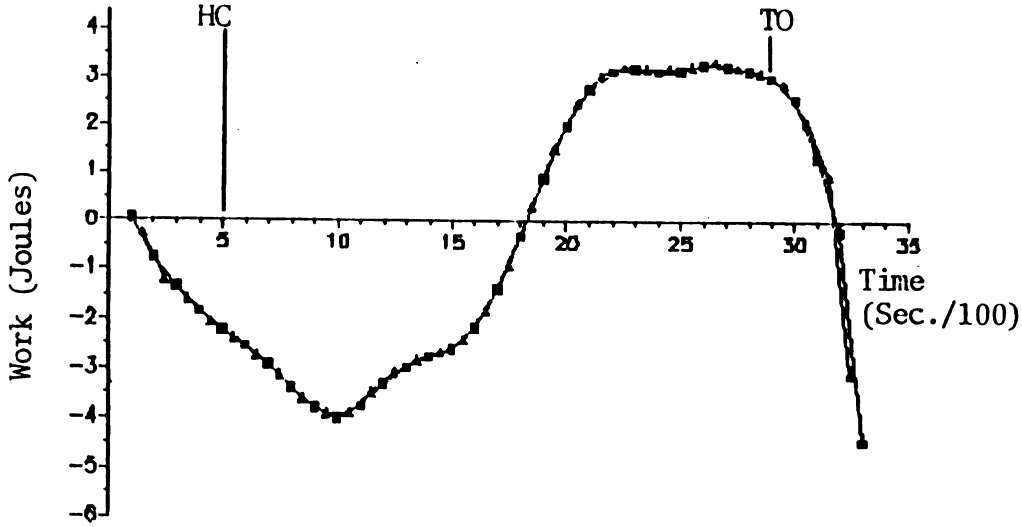


Figure 9a Run #1

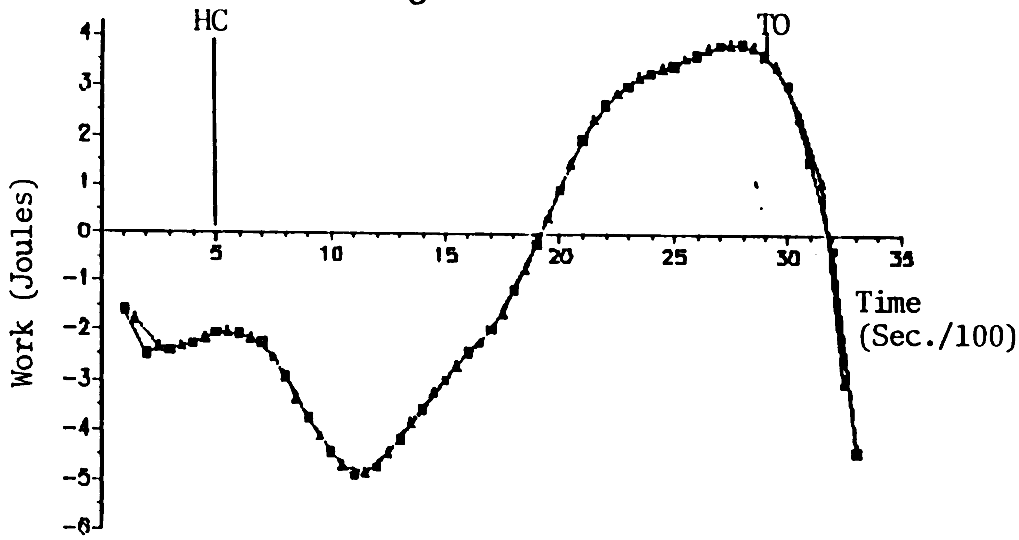


Figure 9b Run #2

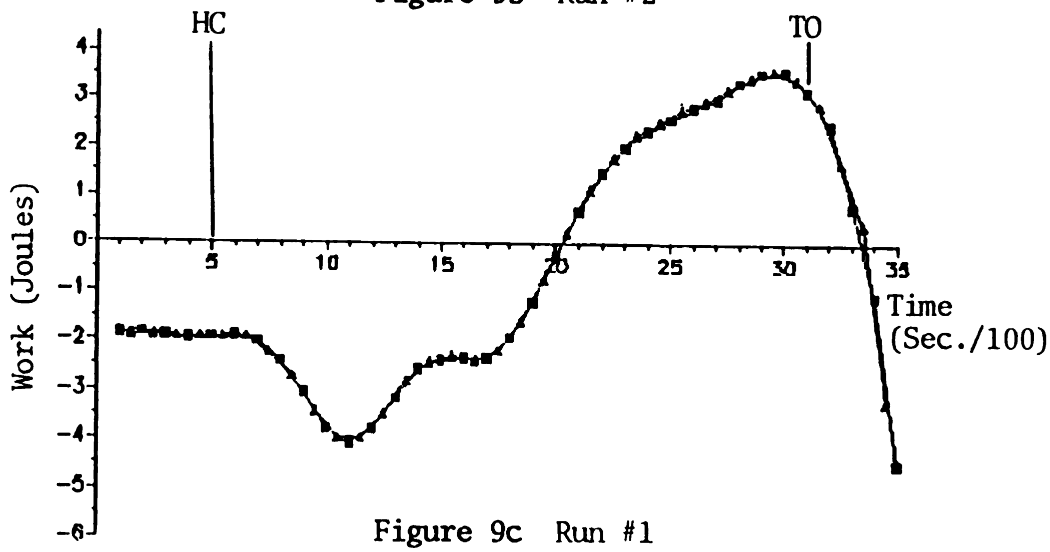


Figure 9c Run #1

Energy Method
Work Method

Figure 9 Work done on the thigh segment.

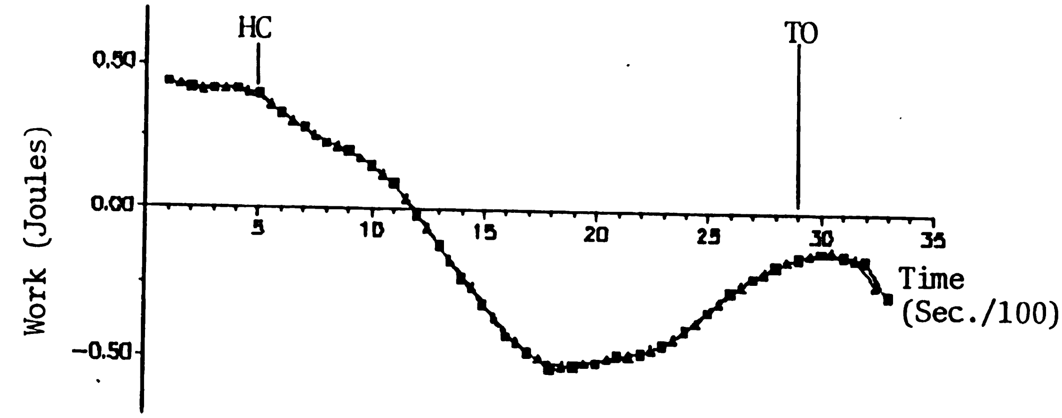


Figure 10a Run #1

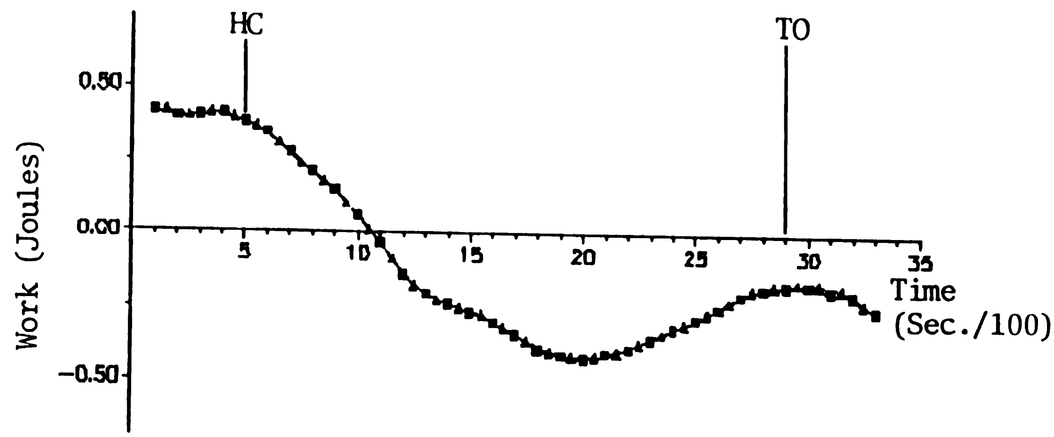


Figure 10b Run #2

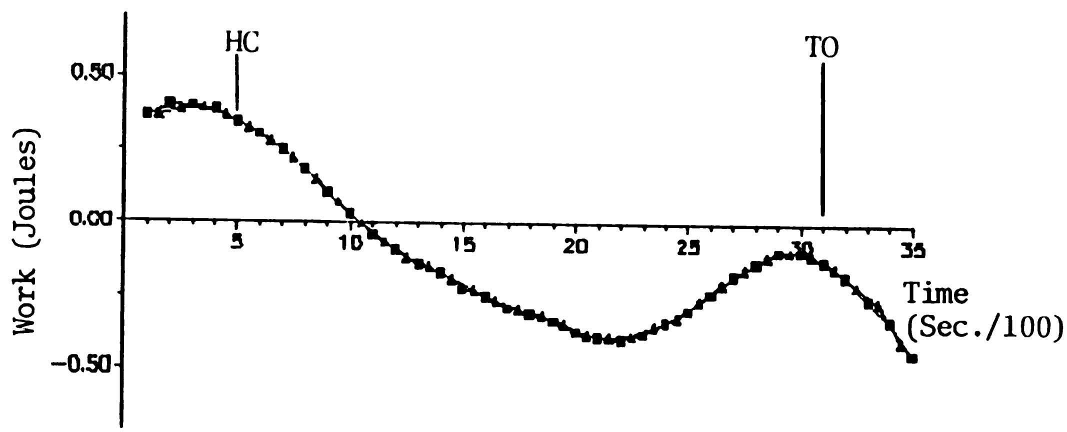


Figure 10c Run #3

Energy Method
Work Method

Figure 10 Work done on the hand segment.

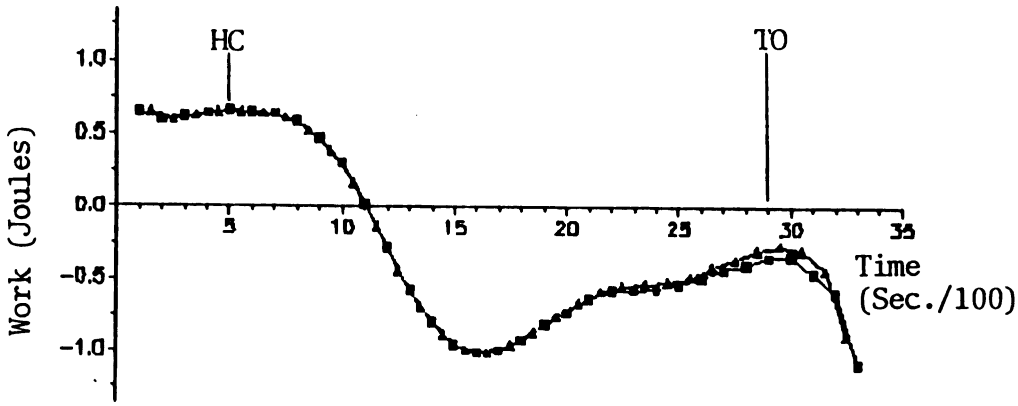


Figure 11a Run #1

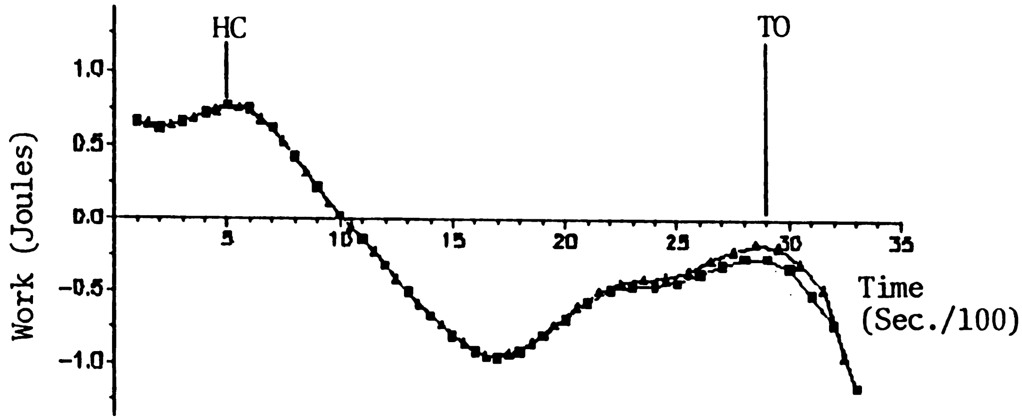


Figure 11b Run #2

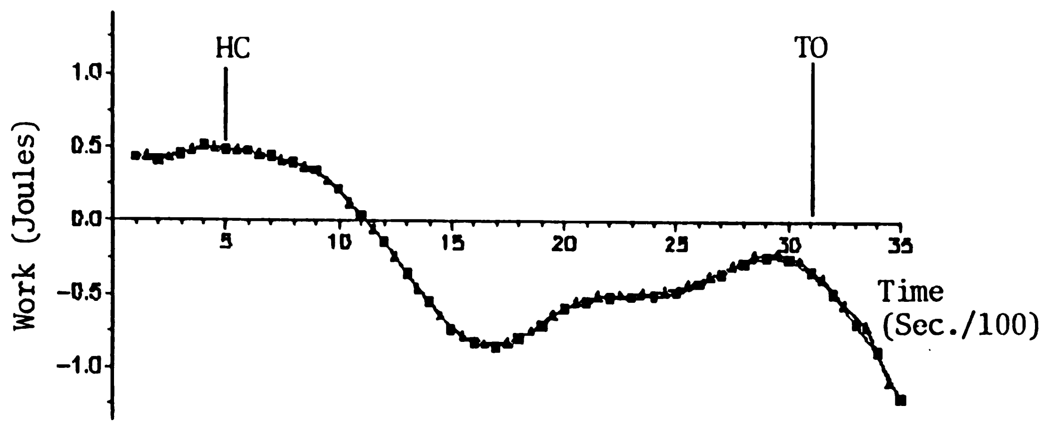


Figure 11c Run #2

Energy Method
Work Method

Figure 11 Work done on the forearm segment.

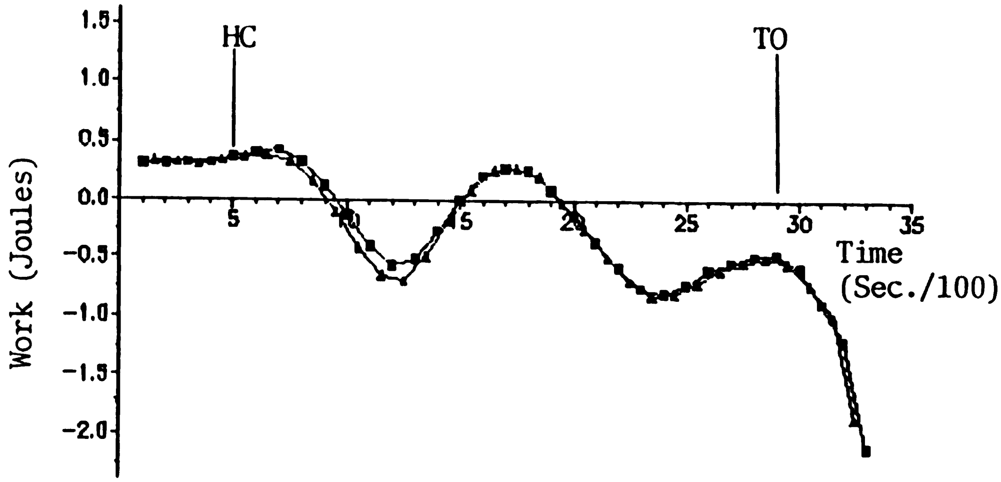


Figure 12a Run #1

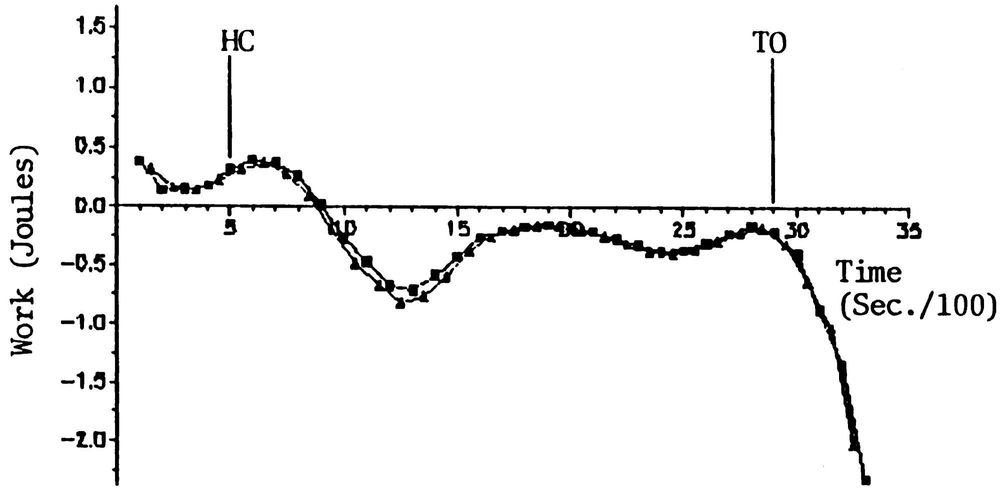


Figure 12b Run #2

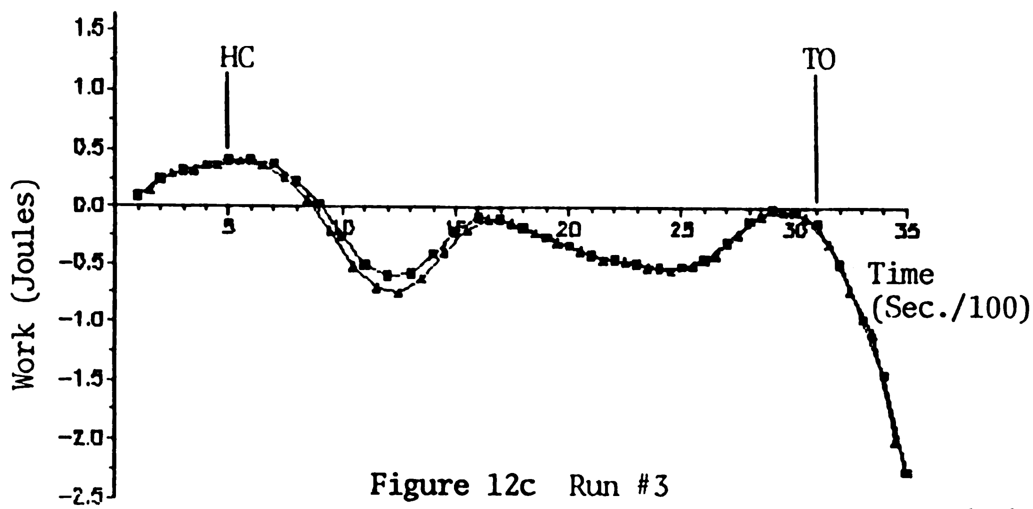


Figure 12c Run #3

Figure 12 Work done on the arm segment.

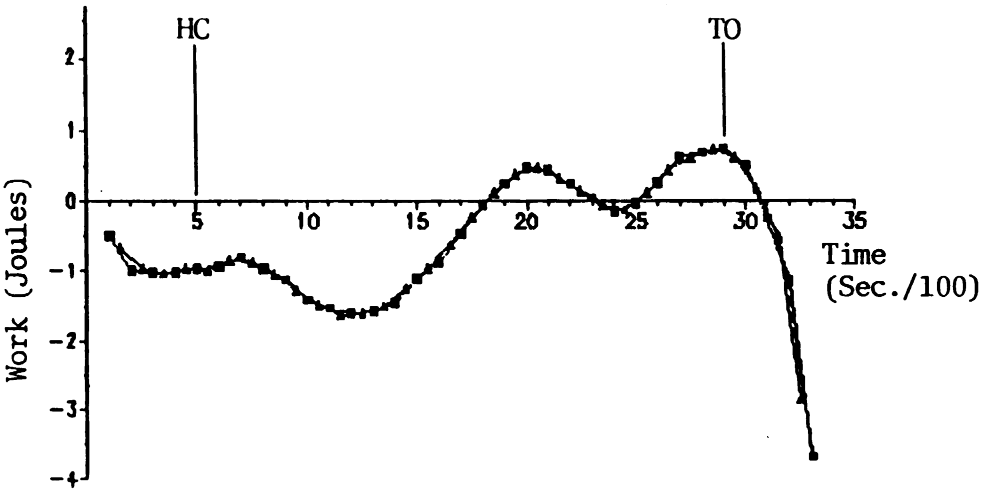


Figure 13a Run #1

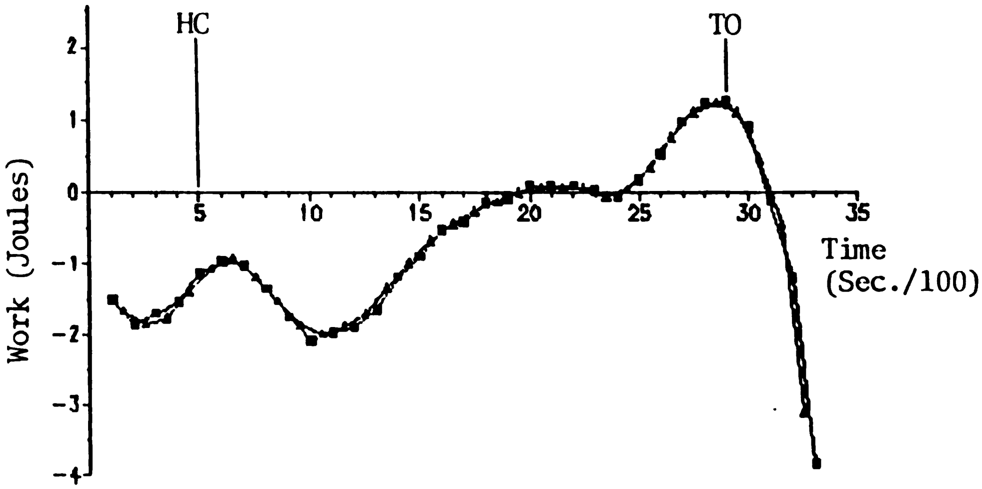


Figure 13b Run #2

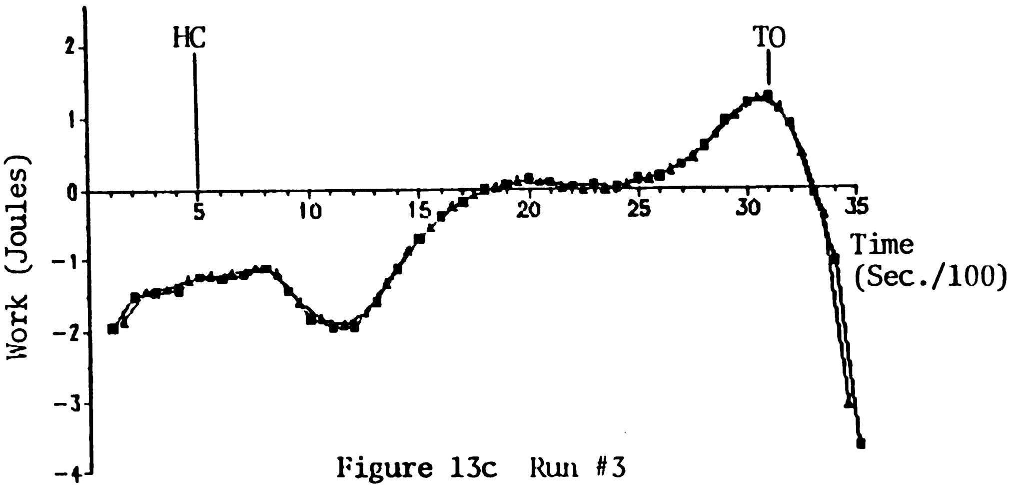


Figure 13c Run #3

Figure 13 Work done on the head-neck segment.

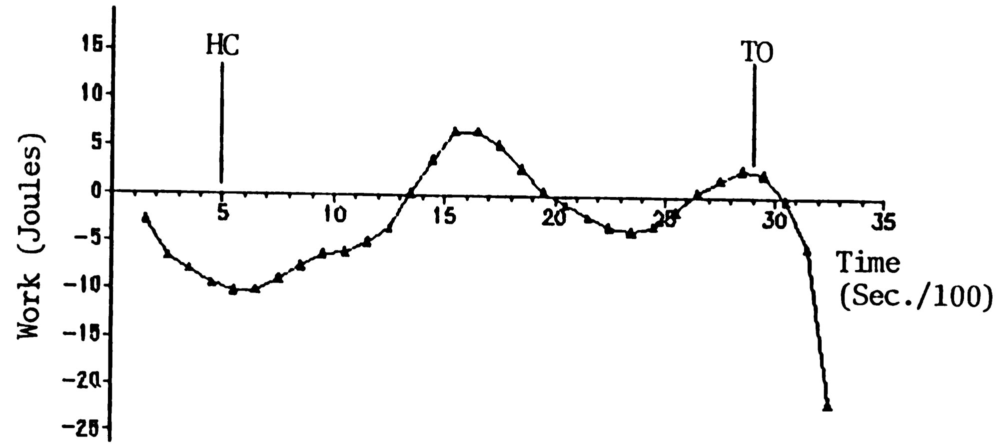


Figure 14a Run #1

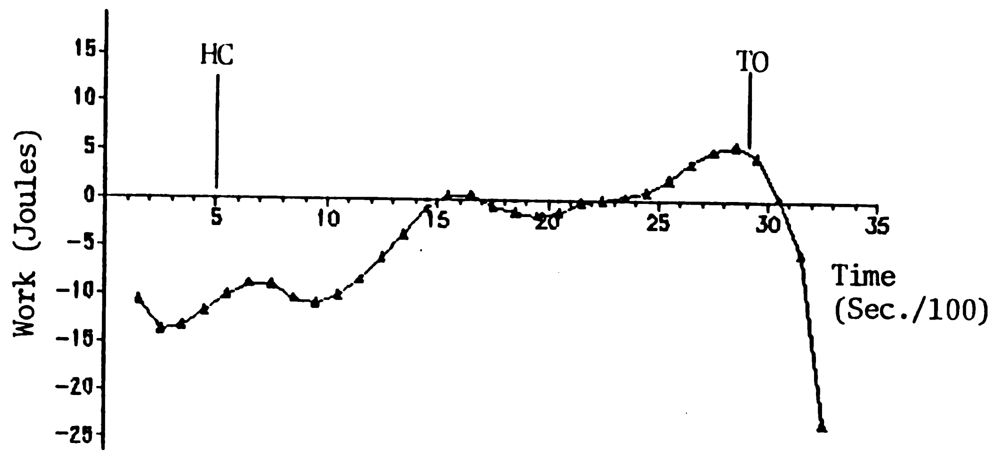


Figure 14b Run #2

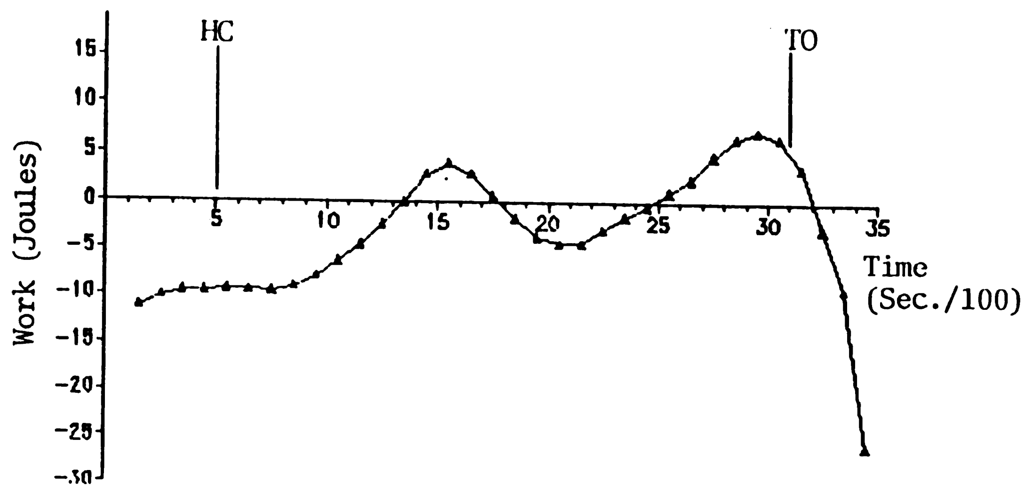


Figure 14c Run #3

Figure 14 Trunk ΔE (work).

done became increasingly negative as these segments were decelerated in their forward swing.

The work done on the trunk calculated by the change in energy of the trunk, is shown in Figure 14. This was not compared to kinetic calculations of work on the trunk since data for the right side of the body was not recorded. The work done on the trunk was similar to the trends noted for the lower limb. Both before heel contact, and for approximately half of stance phase, the work done on the trunk was negative as the trunk decelerated. The remaining half of stance phase is characterized by a double peak. The negative portion of the graph was due to the work done against gravity as the center of gravity of the trunk reached a peak at that time. The final positive portion of the graph peaked near toe off and was followed by a rapidly decreasing amount of work immediately after toe off. These results were consistent with the slopes of the energy for the trunk as published by Williams and Cavanagh (37).

5.2b Joint Muscle Moment Work

The work done by the ankle joint muscle moment is illustrated in Figure 15. At heel contact, the work done by the ankle joint remained near zero. About 0.04 sec after heel contact a large amount of negative work was done, then, approximately half way through the stance phase, this was followed by a large positive work peak which dropped to near zero at toe off. This pattern of work followed the same pattern for power generated by the ankle joint moment as reported by Winter (41) and by Elftman (9).

The work done by the knee joint is shown in Figure 16. In all three trials a relatively large negative work peak followed heel contact, then, again, approximately half-way through stance phase, a positive work peak was found, which dropped to zero about 0.04 sec before toe off. This pattern was similar to the pattern reported by Winter (41), except for a slight positive peak immediately after heel contact. Winter did not report this small peak. The pattern of power generated by the knee joint reported by Elftman (9) followed the same pattern as that of Winter (41).

Figure 17 shows the work done at the hip joint. The work pattern differs from the patterns reported by Winter and by Elftman. However, Winter stated that out of eleven subjects there was no consistent pattern evident for power generated at the hip. The three trials shown in Figure 17 support Winter's statement. Even within the same subject, the only consistent pattern was a large negative work peak immediately after heel contact.

The work done at the shoulder and elbow joints is shown in Figures 18 and 19, respectively. The work done followed the same basic trends as reported by Elftman (9). The work done at the shoulder was positive before heel contact but became negative about 0.04 sec. after heel contact. Thus it appeared that the work done at the shoulder caused the arm to decelerate as it swung forward through stance phase. The subject filmed for this data had large out of plane motions for his forearm. Although he was requested to limit the motion as strictly as possible to the sagittal plane, the left forearm would consistently swing medially after left toe off. Thus the work done by the elbow joint shown in Figure 19 is probably not an accurate representation of the

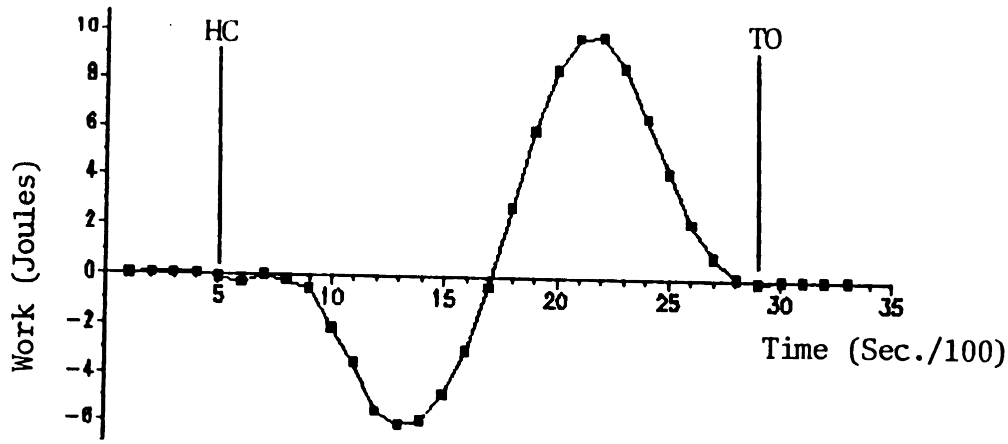


Figure 15a Run #1

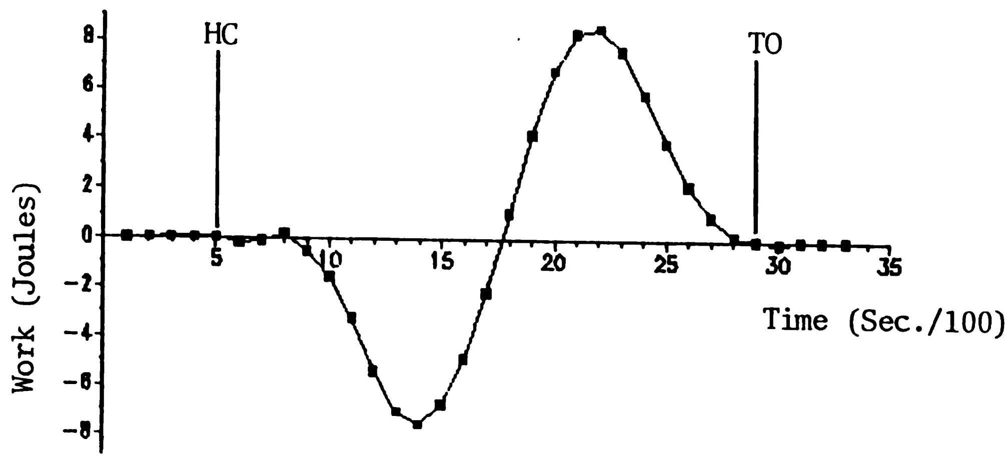


Figure 15b Run #2

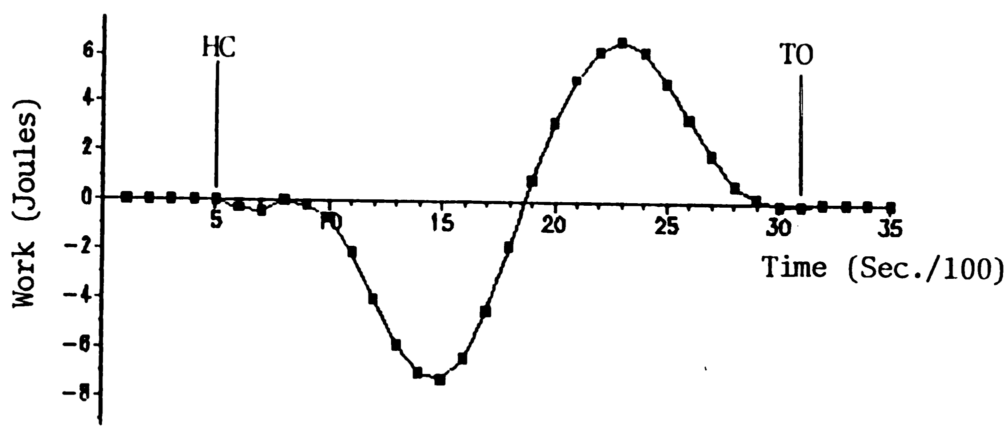


Figure 15c Run #3

Figure 15 Ankle joint work.

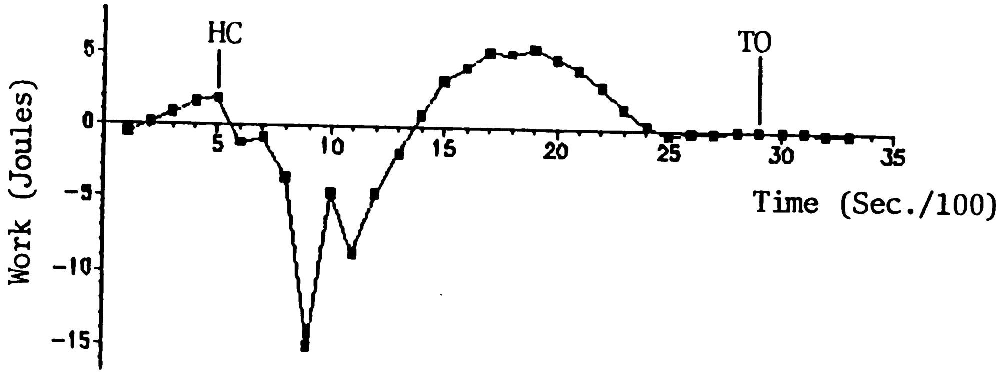


Figure 16a Run #1

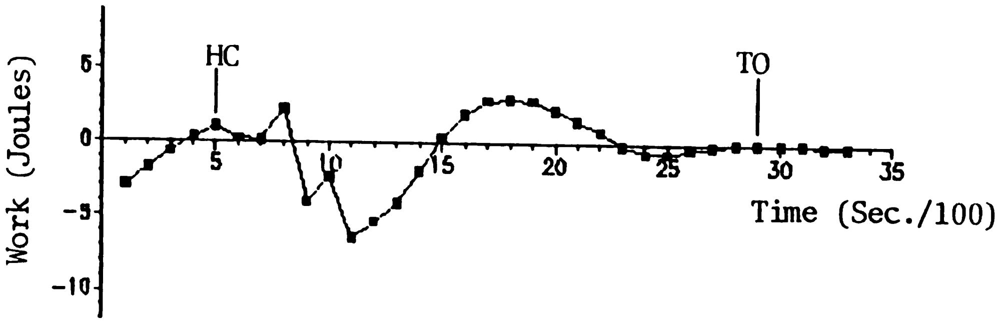


Figure 16b Run #2

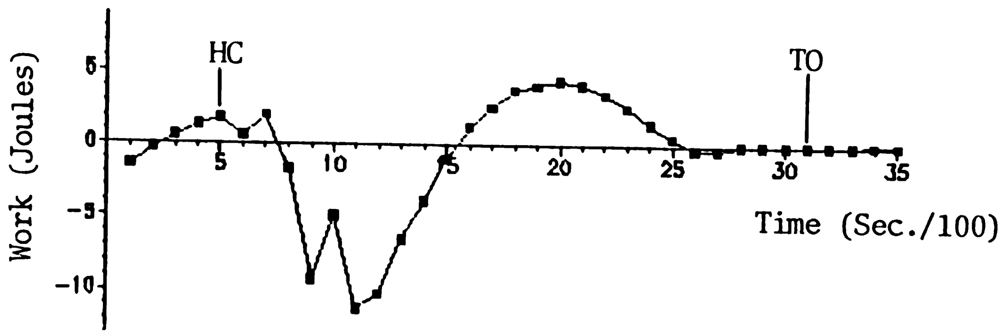


Figure 16c Run #3

Figure 16 Knee joint work.

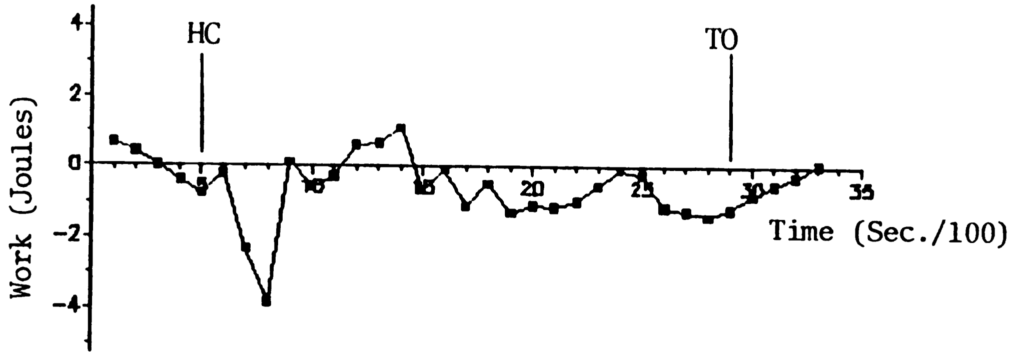


Figure 17a Run #1

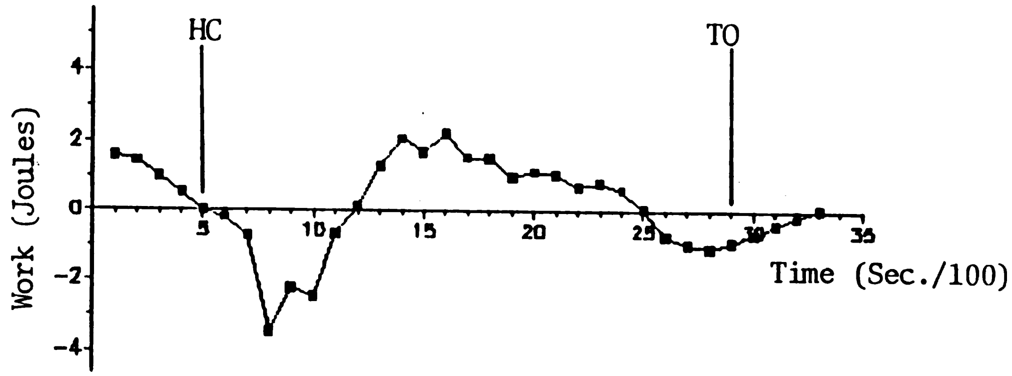


Figure 17b Run #2

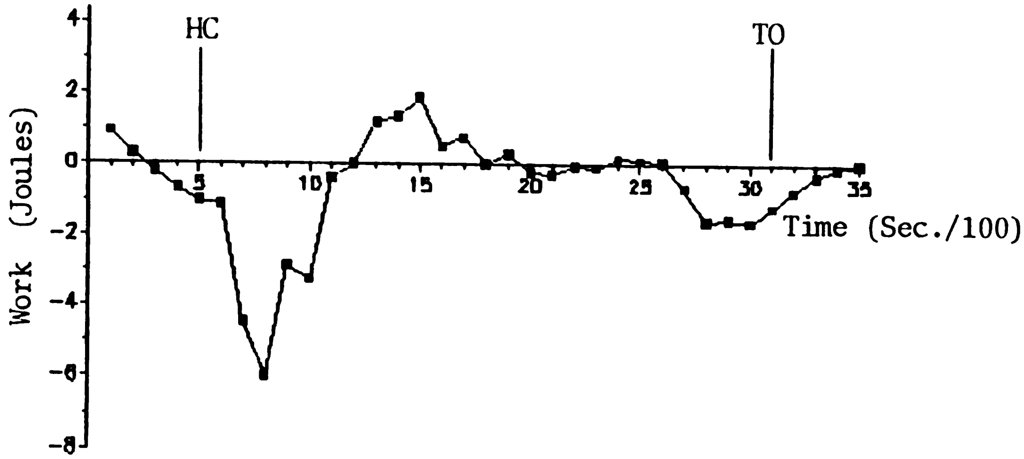


Figure 17c Run #3

Figure 17 Hip joint work.

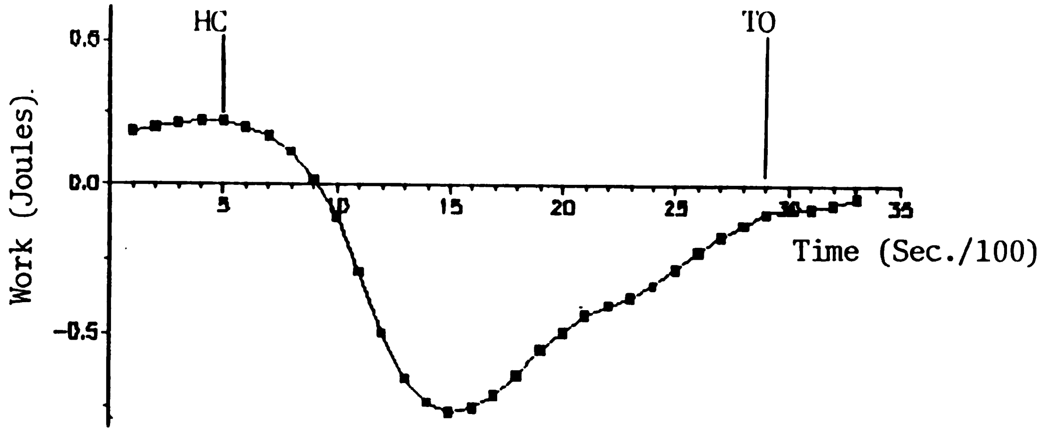


Figure 18a Run #1

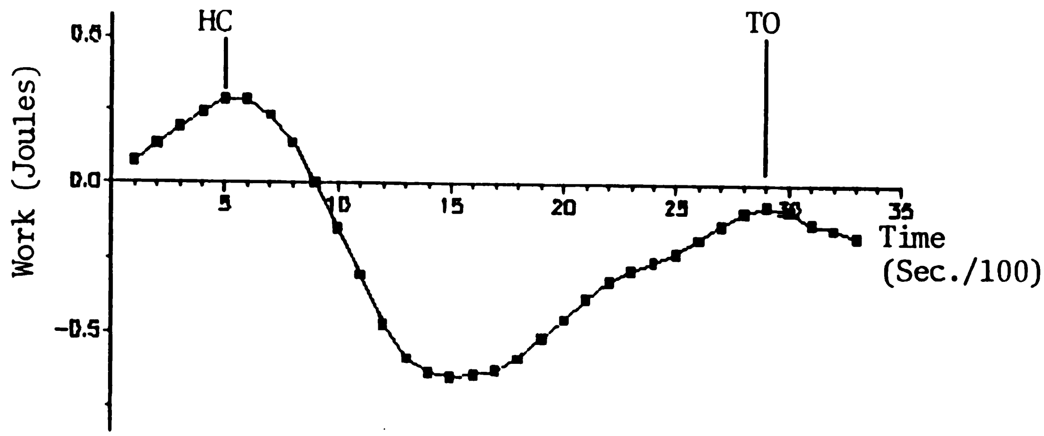


Figure 18b Run #2

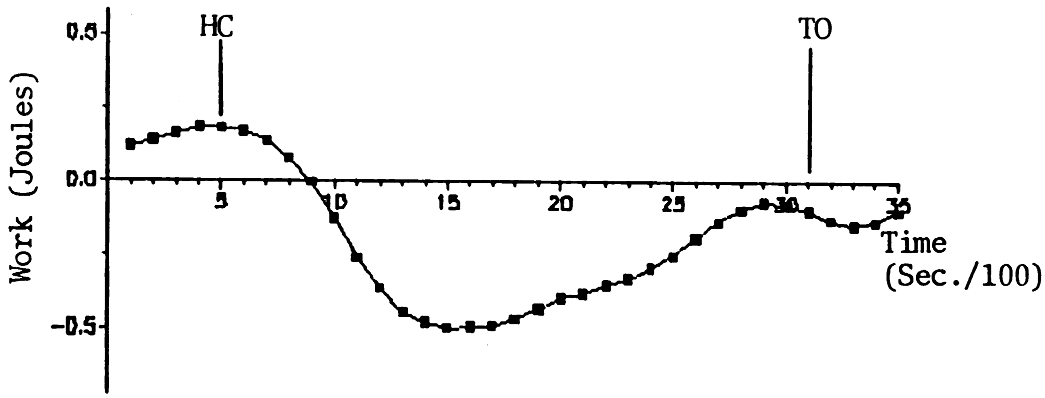


Figure 18c Run #3

Figure 18 Shoulder joint work.

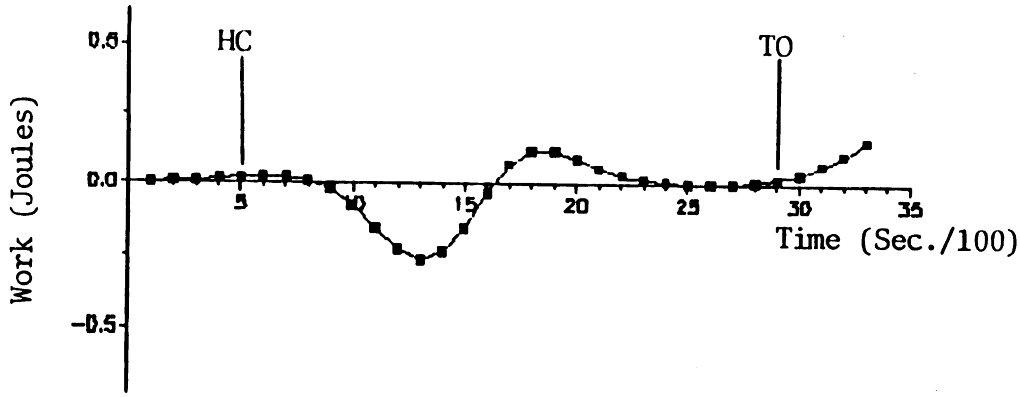


Figure 19a Run #1

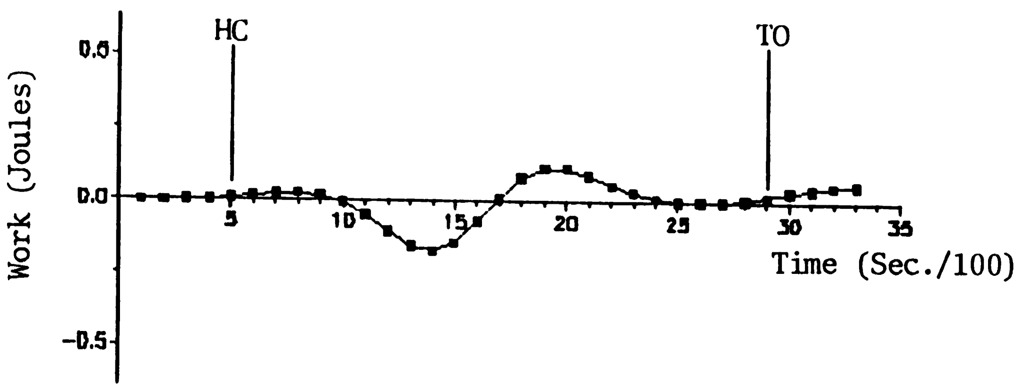


Figure 19b Run #2

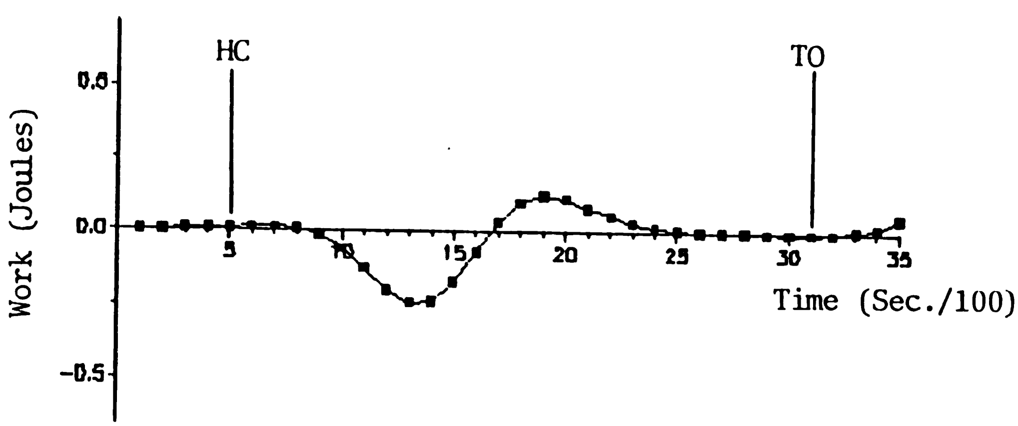


Figure 19c Run #3

Figure 19 Elbow joint work.

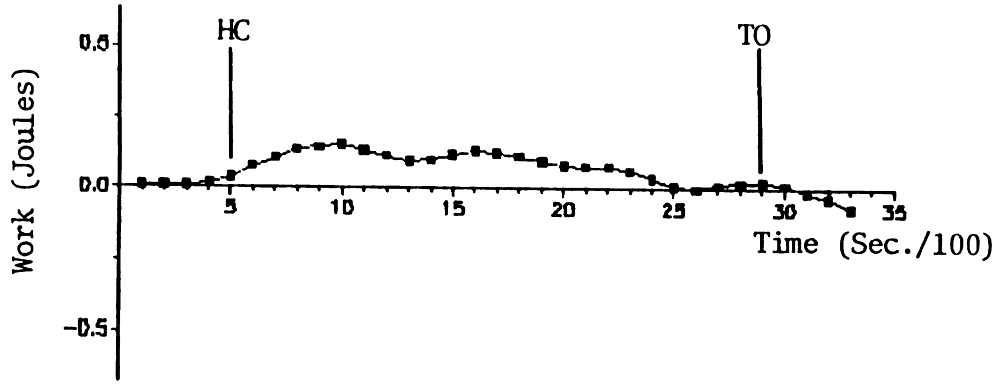


Figure 20a Run #1

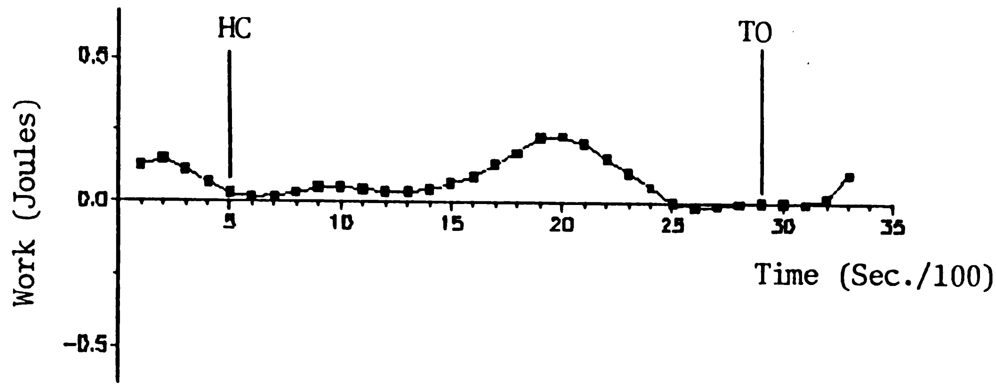


Figure 20b Run #2

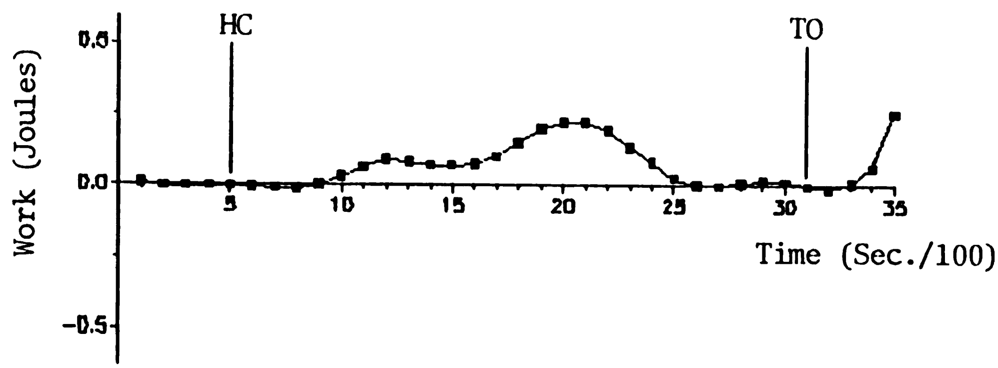


Figure 20c Run #3

Figure 20 Neck joint work.

actual work done at that joint. However, as would be expected, the work done by these joints is small compared to the work done by the joints of the lower limb.

The work done by the neck "joint" is illustrated in Figure 20. No comparison was available in the literature for this "joint". No pattern was consistent within the three trials. The work done by this joint was small compared to the work done by the lower limbs.

5.2c **Total Work:**

The total work done by the joint muscle moments of the left side of the body, including the neck, was calculated using equation (36) and is shown in Figure 21. For comparison, the sum of the segmental energy changes (W_E) is shown in Figure 22 as well as the method of Norman, et al (28) (W_n), the method used by Winter (40) (W_{wb}), and the method utilized by Pierrynowski, et al (29) (W_w).

As indicated by the sum of the absolute value of the joint work found in Figure 21, the work done by the muscles of the left side of the body was on the order of 200 joules for the stance phase of running for this subject. Since Figure 21 represents the absolute value of joint work summed over time, a steeper slope indicates a greater rate of work being done. The slope of the total joint work curve is steepest between heel contact and toe off. This slope indicates that the majority of work is done during stance phase. Very little work is done before heel contact and after toe off. This is what would be expected since stance

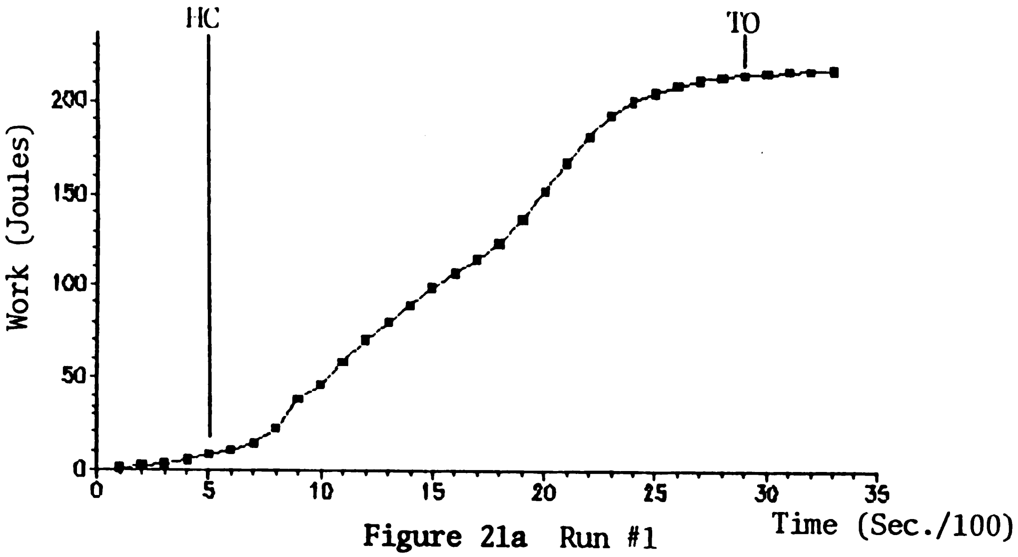


Figure 21a Run #1

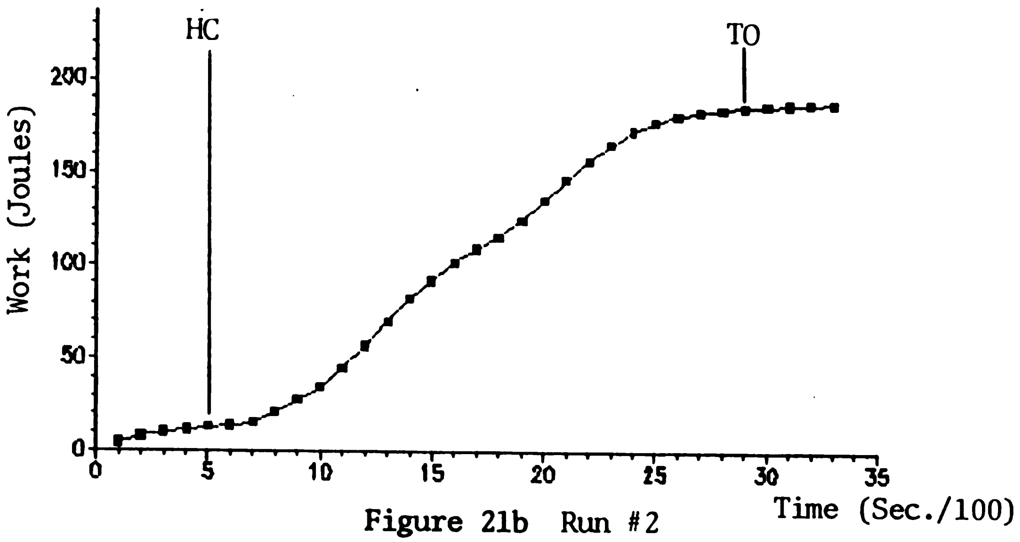


Figure 21b Run #2

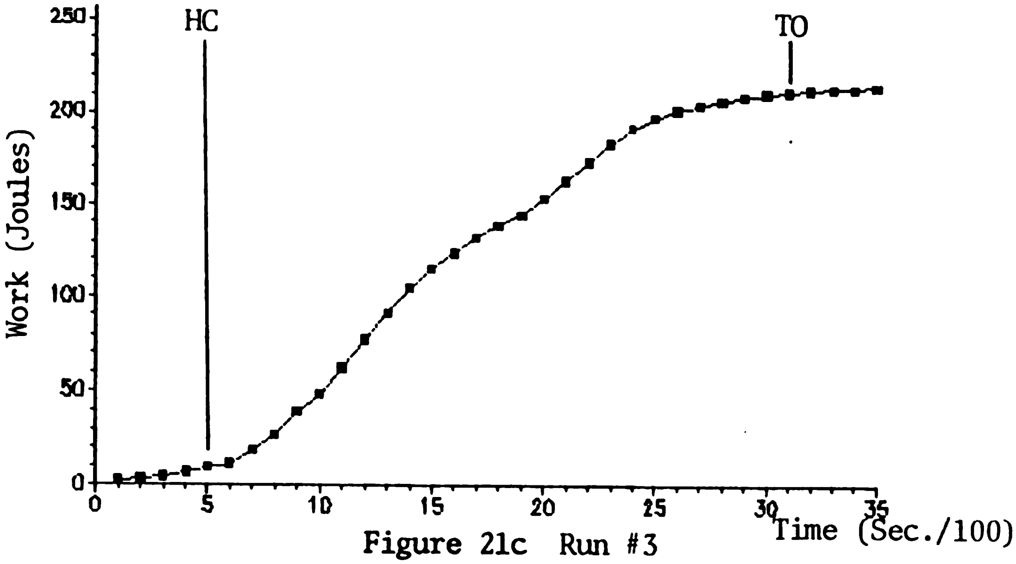


Figure 21c Run #3

Figure 21 Total absolute joint work.

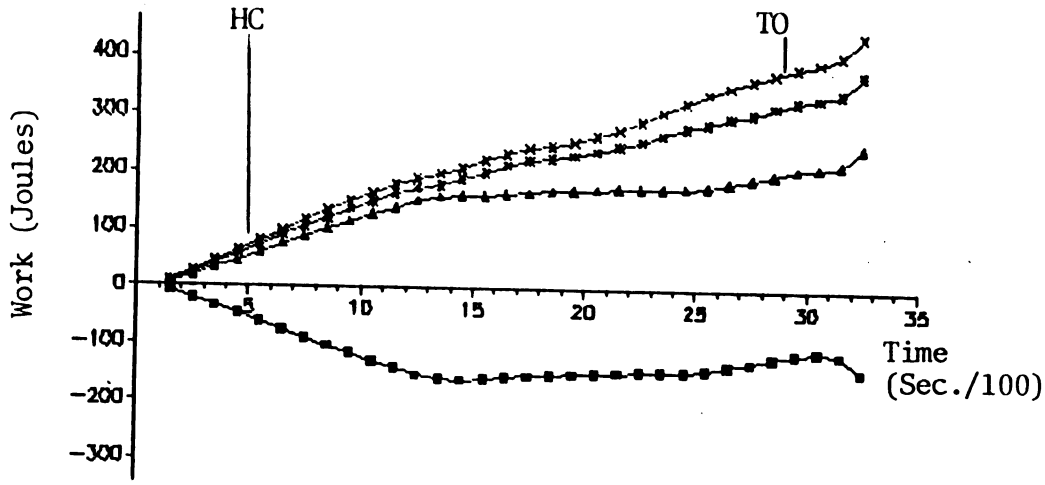


Figure 22a Run #1

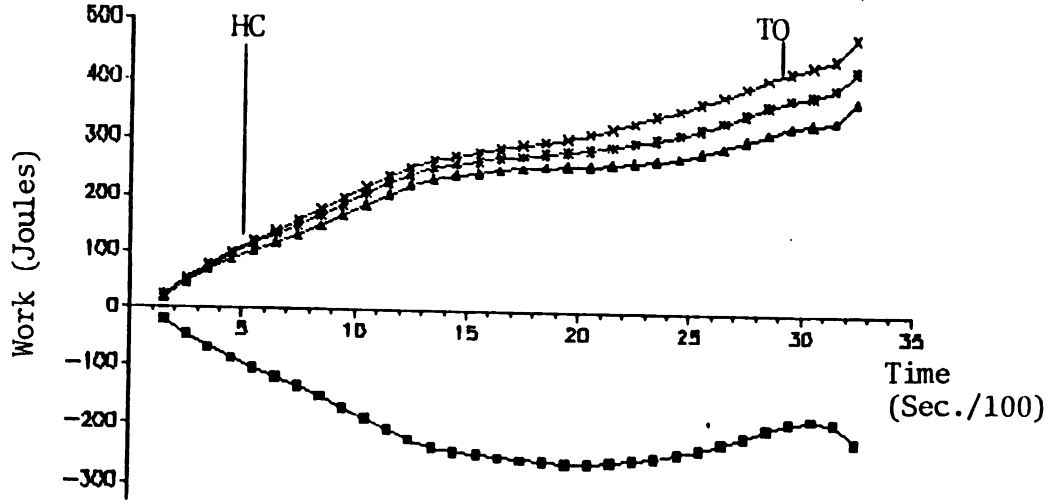


Figure 22b Run #2

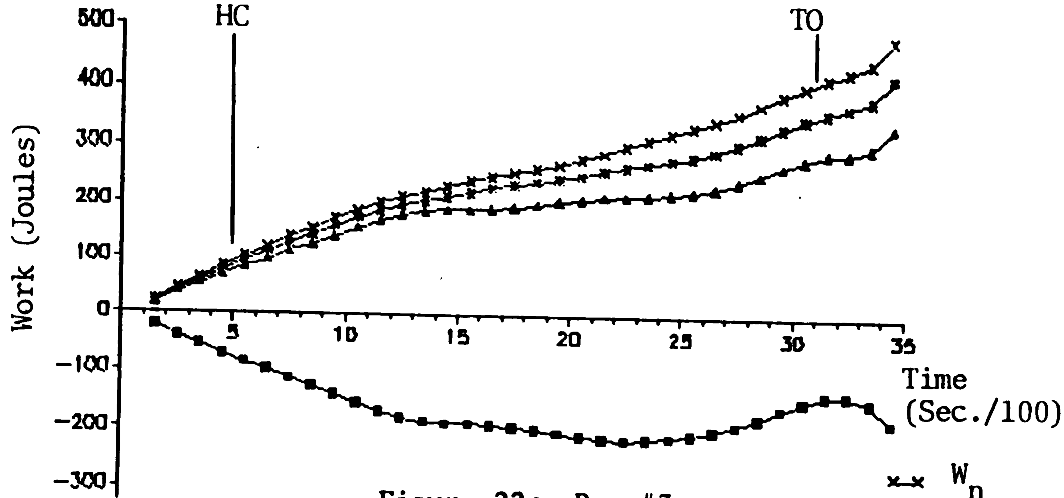


Figure 22c Run #3

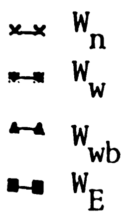


Figure 22 Total work calculated by four energy methods

phase is the only phase during which energy is added to the body by the propulsion of the muscles of the lower limb.

A comparison between the energy methods of Figure 22 to the joint work method of Figure 21 would be difficult. The analytical discussion showed great differences in the relationship of each of the methods to the physical work done by the muscles and joint reaction forces. The results of the energy methods differed from each other and from the joint work method.

The results of the four energy methods, shown in Figure 22, include the change in energy of the trunk. Thus, indirectly, these methods included work done on the trunk by the right hip and shoulder. Since data collection and analysis was limited to the left side of the subject, the kinetic data for the right hip and shoulder were not available. This lack of data created an additional problem concerning the comparison of the methods. Although the final values for some of the energy methods appear close to the final values of the joint work method, this was merely a coincidence.

As would be expected by the definitions of W_n, W_w, and W_{wb}, the value obtained for W_n was the largest of the energy methods calculated, followed by W_w, and W_{wb}. In Figure 22, W_E (defined in equation (41)) was negative throughout stance phase. This negative energy change indicated a deceleration on all segments until near toe off. At toe-off, the slope of the total energy curve was positive, indicating that the body was gaining energy.

CHAPTER VI

CONCLUSIONS

The purpose of this study was to investigate the methods of calculating mechanical work as they apply to the study of human efficiency. Segmental energy methods have been shown to be inadequate for calculating muscle moment work. The model used in this study was found to be an improvement over the previous methods presented in the literature. However, this model also has several limitations:

1) The relative efficiency of negative and positive work was not taken into consideration.
2) The elastic component of muscle can do work but its effects were not considered in this thesis.
3) Isometric contractions and antagonistic muscle contractions were ignored.
4) The effect of multi-joint muscles were not considered.
5) Studies are limited to planar motion, restricting the types of motion that can be investigated.

The concept of human efficiency is to provide a normalized quantity to allow the comparison of new athletic (or prosthetic) equipment, techniques, and styles. Sensitivity and reliability are essential. Unfortunately, normalizing mechanical work with metabolic energy does not provide a very sensitive method for measuring efficiency. As is apparent by the limitations listed above, further study of mechanical work calculations is needed to improve the sensitivity of measurement. The metabolic energy consumed for a given event is difficult to differentiate from resting respiration and requires bulky equipment that limits the type of motion that can be studied.

Other methods of normalizing mechanical work must be considered. Hubley and Wells (21) normalized work done at each joint with the total absolute value of work done at all joints and compared the ratio of work done at each joint.

The underlying concepts of human efficiency need further questioning and study. If mechanical work is used as the numerator for calculating human efficiency, the sensitivity of measuring mechanical work must be improved. It must then be normalized by a parameter that is both physically meaningful but yet sensitive enough to pick up the effects of minor changes in the equipment or technique being studied.

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