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Mechanical work output and energy transfers of female cross-country skiers.

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MECHANICAL WORK OUTPUT AND ENERGY

TRANSFERS OF FEMALE CROSS-COUNTRY SKIERS

By

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A Thesis
submitted to the
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MECHANICAL WORK OUTPUT AND ENERGY TRANSFERS
OF FEMALE CROSS-COUNTRY SKIERS

ABSTRACT

Examination of energy curves and work output can provide insight into the efficiency of a performance. The purpose of this study was to determine the internal mechanical work output and energy transfers of female cross-country skiers. The skill analyzed was the diagonal stride technique.

The sample consisted of three international level female cross-country skiers and three provincial level skiers. High speed cinematography in conjunction with a computerized analysis of data was utilized. Based on equations developed by earlier researchers, the energy analysis yielded mechanical work values accounting for energy transfers within and between body segments. From these terms, the magnitudes of energy transfer within and between segments were also calculated.

The international level skiers were found to ski at a higher velocity than the provincial level skiers. Subsequent analysis revealed significant differences in the total amount of energy transferred. The separate components,

between and within energy transfers, although much higher for the international level skiers, did not differ significantly. An analysis of individual body segment transfers revealed no significant differences to exist between the groups.

Examination of the energy curves showed the elite skiers to exhibit higher levels of potential and kinetic energy for nearly every segment. Possible explanations for these higher values were discussed in an attempt to account for the increased velocity.

DEDICATION

This work is dedicated to Loretta Menard, for making sure I did my homework so many years ago, and for teaching me how to pray. Thanks, Mom.

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I wish to express my sincerest appreciation to
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CHAPTER I

INTRODUCTION

The analysis of human movement often involves a comparison between a model performance and an actual performance. Whether this comparison be qualitative or quantitative, the variables which such evaluations are based upon are many, and recently, efficiency has become a major comparative measure in the analysis of performance.

Efficiency can be defined as "the ratio of effective work to the energy expended in producing it". A lack of compliance with this definition has lead to reporting of erroneous results (Cotes and Meade, 1960; Gaesser and Brooks, 1975).

The calculation of efficiency require a measure of mechanical output, equivalent to the mechanical work performed during a task, divided by the metabolic cost of the work. The total work involves the accurate calculation of internal as well as external work. External work has been defined as "the fraction of total mechanical work necessary to sustain the displacement of the center of gravity" (Cavagna et al, 1964). Earlier researchers assumed external mechanical work to be the sum of the work done both at each step against gravity and of that due to velocity changes in the forward direction (Fenn, 1929). Difference among studies have revolved around the

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calculation of the internal work value. Fenn, (1929), a fore-runner in energy analysis, disregarded the existence of energy transfer mechanisms within and between body segments, consequently arriving at spuriously high total mechanical work. The techniques used by Margaria (1963) produced negative mechanical work values as a result of the inaccurate assessment of the work performed. In a later study by Cavagna et al (1966), the trajectory of the body's center of gravity was assumed to contain the information needed for the determination of mechanical efficiency. However such a supposition does not account for the reciprocal movements of the limbs and underestimates the actual work value (Caldwell, 1980). Clearly the position of the body's center of gravity may remain relatively constant regardless of the work done by the limbs.

In dealing with the anomalies associated with past studies, Winter (1979) proposed a procedure which eliminates errors inherent in the techniques previously used.

Mechanical Energy and Work

Mechanical energy has been subdivided into two parts: external energy and internal energy. External mechanical energy is that which moves the body against external forces. Internal mechanical energy is that which moves the limbs through a specific movement pattern. When combined with all work output calculations, mechanical energy is a kinetic analysis which is both physiologically and mechanically sound.

The assessment of the energy involved in human movement requires an accurate measure of the mechanical work completed.

The basis of any internal mechanical work calculation is a total body energy-time curve (Winter, 1979). The total energy can be calculated from the instantaneous energy level of each segment summed over one movement cycle. The total energy of the body is reflective of the mechanical work output.

Energy is stored in one of two forms: kinetic energy and potential energy. Potential energy, due to the force of gravity, increases with the height of the body above some reference datum. Kinetic energy, is the energy of motion, and can be further divided into two components: translational kinetic energy and rotational kinetic energy. The former is energy stored as a result of the linear velocity of a body's center of mass. The latter is a function of the angular velocity of the body in a given plane. The two forms of energy storage are presented in equations 1 - 3.

$$P.E. = MGH \qquad (Eq. 1)$$
where P.E. = Potential Energy
M - mass
G - acceleration due to gravity
H - height

$$K.E. = \tfrac{1}{2} MV^2 \qquad (Eq. 2)$$
where K.E. = Translational Kinetic Energy
M - mass
V - velocity

$$R.K.E. = \tfrac{1}{2} Iw^2 \qquad (Eq. 3)$$
where R.K.E. = Rotational Kinetic Energy
I - rotational moment of inertia
w - angular velocity

The internal mechanical work ouput is calculated by summing the absolute cahnges in energy levels over a period of time. Such a procedure considers both increases and decreases in energy levels, thereby accounting for the metabolic cost of negative work. An increase in the energy level of a segment represents a phase of positive work. Consequently, a decrease in the energy level indicates a phase of negative work. Since changes in energy delineate work done, oscillations should be minimal. Equations used in earlier studies used this method by nonetheless yielded high work output values (Norman et al, 1976). The basic method to be used in this study is defined in equation 4 as Wn, and assumes no energy transfer between or within segments.

$$Wn = \sum_{i=1}^{s} \sum_{j=1}^{F} (|PE_{ij} - PE_{ij-1}| + |KE_{ij} - KE_{ij-1}| + |RE_{ij} - RE_{ij-1}|)$$

i,s - segment
j,f - frame
(Equ. 4)

Wn - mechanical work assuming no energy transfer

Energy transfer

Two forms of energy transfer occur during a movement. A transfer within body segments occurs when there is an exchange between the kinetic energy level and the potential energy level. Such a transfer is especially evident in gait studies (Cavagna et al, 1966; Winter, 1979; and Ralston et al, 1968), where a rise in the potential energy level was

accompanied by a fall in the kinetic energy level. The occur-
rence of this phenomena is best illustrated by the action of
a swinging pendulum (Fig. 1), (Smith, 1975). At the top of its
swing, a pendulum has maximum potential energy and zero kinetic
energy. The reverse is true when the pendulum is at the bottom
of its swing. In such a case, the total energy is held at a
constant, that is the total value of the potential and kinetic
energy levels remains the same even though changes are occurring
in the separate levels. As illustrated in Fig. 1, such a situ-
ation can occur within a swinging limb.

A transfer of energy between segments occurs when one
segment is exerting force on another segment during a trans-
lational movement. One example of such a transfer is the
acceleration of the shank which occurs when the thigh decel-
erates (Fig. 2), (Smith, 1975).

The study of mechanical work output demands that the
calculations used be based on certain assumptions. Researchers
in the past have overlooked these assumptions, resulting in
rather inaccurate determinations of work output. One such
premise is that energy transfer occurs within and between body
segments, and must therefore be accounted for.

Winter (1979) presented a definition of mechanical work
which accounts for between and within body segment transfers,
as well as all potential and kinetic energy components, and
both positive and negative work done by the muscles. The
equation, when used in conjunction with the Wn equation pre-
sented by Norman et al (1976), permits the calculation of the

Maximum
Potential
Energy

Maximum Kinetic Energy

Joint center
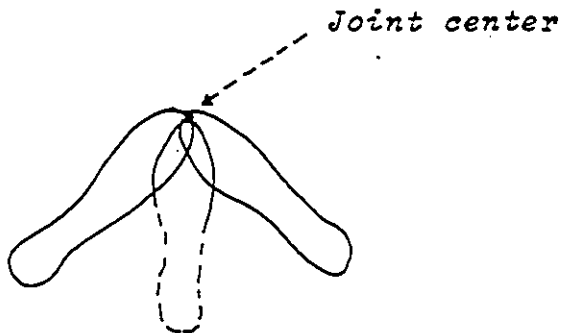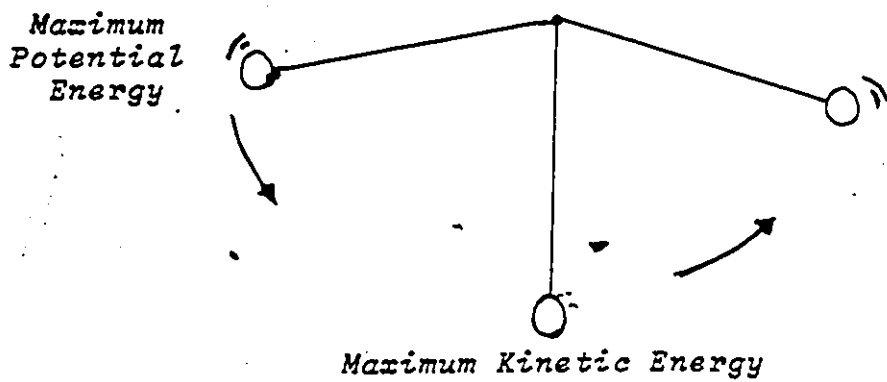
Figure 1:   Diagram of a frictionless pendulum
             illustrating within segment transfers

(Smith,1975)
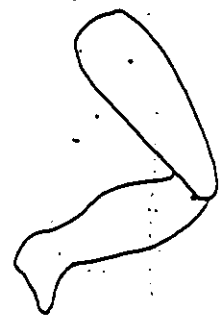
Thigh and shank
accelerating forward
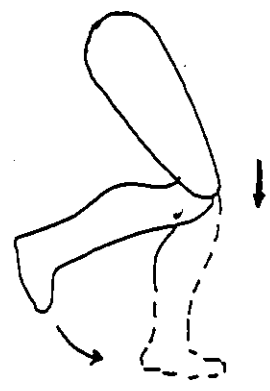
Transfer of energy from
thigh to shank as thigh
decelerates

Figure 2: Diagram illustrating between segments transfers.

(Smith,1975)

magnitude of energy transfers both within and between segments (Pierrynowski et al, 1980). In a similar manner, the magnitudes of within and between energy transfers can be calculated separately.

The total mechanical energy level of any segment at any one point in time can be defined by Equation 5:

$$E_i = M_i GH_i + \tfrac{1}{2}M_i V_i^2 + \tfrac{1}{2}I_i w_i^2 \quad \text{(Eq. 5)}$$

or

$$E_i = PE_i + KE_i + RKE_i$$
$$\text{i-segment}$$

The summation of segmental energies at each point in time yields a total body energy curve as noted in Equation 6.

$$TE_i = (PE_{ij} + KE_{ij} + RKE_{ij}) \quad \text{(Eq. 6)}$$

TE - Total body energy curve

The internal mechanical work output, assuming energy transfers between and within segments, can be calculated by summing the absolute changes of the total body energy curve over time, as seen in Equation 7.

$$Wwb = \sum_{j=1}^{F} \left\{ \sum_{i=1}^{S} (TE_{ij} - TE_{ij-1}) \right\} \quad \text{(Eq. 7)}$$

i,s - segment

j,F - Frame

Wwb - Mechanical work assuming energy transfer within and between segments

A further calculation can be made based on the assumption that potential and kinetic energy can be transferred within segments but that no transfer occurs between segments. Such a method requires the addition of PE, KE, and RKE values to give a total energy curve for each segment. The absolute differences in energy levels of all segments are then summed, as noted in Equation 8:

$$Ww = \sum_{i=1}^{s} \sum_{j=1}^{F} |(TE_{ij} - TE_{ij-1})|$$

i,s – segment

j,F – Frame

Ww – Mechanical work assuming energy transfer within segment

The magnitude of energy transfer and mechanical work values can be subsequently determined. By subtracting the work done which assumes both within and between energy transfer from the work done which assumes no energy transfer, the magnitude of energy transfer exchanged within and between segments can be derived.

$$Twb = Wn - Wwb \qquad (Eq. 9)$$

Twb – Energy transferred within and between segments

Similarly, by subtracting the work value which assumes both within and between energy transfer from that which assumes only within segment transfer, the amount of energy transferred between segments can be determined.

$$Tb = Ww - Wwb \qquad (Eq. 10)$$

Tb – Energy transferred between segments

Finally, the amount of energy transferred within segments can be determined through simple subtraction as noted in Equation 11:

$$Tw = Twb - Tb \qquad (Eq. 11)$$

Tw - Energy transferred with segments

Energy transfers allow the body to repeatedly utilize the metabolic energy created during a movement. A performer who can transfer energy from one form of storage to another will produce the movement with less metabolic cost than a performer who's mechanisms for energy transfer are less effective. Consequently, less metabolic energy would be needed, thus increasing the overall mechanical efficiency of the performer.

This study investigated the mechanical work outputs, energy patterns, and energy transfers as a reflection of skill level. Both concentric and eccentric muscle activity have a metabolic cost, thus affecting the mechanical work output values. For this reason, a movement which is distinguished by the presence of many internal and external forces was examined. The movement selected was the diagonal stride technique used in cross-country skiing. It was anticipated that such an analysis would contain useful diagnostic information relevant to the ideal performance of the diagonal stride technique.

Statement of the Problem

The purpose of the study was to determine the magnitudes of internal mechanical work and energy transfer values in

elite and skilled female cross-country ski racers. More
specifically, the study included an assessment of the fol-
lowing kinematic and kinetic variables evident in the diago-
nal stride techniques of elite and skilled female cross-
country skiers:

1. Horizontal and vertical velocity components of
   limbs

2. Potential energy components of each body segment

3. Kinetic energy components of each body segment

4. Total body energy levels

5. Energy exchanges within each segment

6. Energy exchanges between segments

7. Internal work values

The study relates the mechanical energy and work output
values of the skiers to the three phases of the diagonal
stride. A comparative analysis of the energy curves of the
elite skiers versus those of the skilled skiers follows.
The review of literature examines the above mentioned para-
meters as to their relevancy in the analysis of mechanical
energy, work output, and the diagonal stride technique.

Limitations

Numerous limitations exist within any form of biomechanical
research, and as such, a variety of conditions must be satisfied
in order to minimize the overall effects of the limitations.

The limitations of the present study can be divided into
three categories: cinematographical, measurement and assigned.

The complexity of human movement requires the use of some

imaging system in capturing the motion for analysis. The system used in this study was a 16 mm Locam camera operating at 100 frames per second. The objectivity and validity of measuring actual body movement from projected images presents many limiting factors in itself. However, through identification of the sources of error and the subsequent employment of rigid experimental procedures, error which is inherent in filming can be minimized.

Errors due to distortion were limited through proper placement of the camera in the filming area. A suitable image size is required for the reduction of data. The camera however was placed far enough from the subject to minimize perspective error. The farther the camera is from the subject, the more likely the body segments will be an equal distance from the optical lens.

A second source of perspective error is found in sport skills where movement about the transverse axis occurs. Filming procedures record movement in one plane and lateral movements are not quantifiable. The nature of the diagonal stride facilitates the recording of movement in one plane as most movements occur in the sagittal plane. The arms and legs move parallel to the ski track in an exaggerated walking stride which allows for relatively little rotation of the hips and shoulders (Titley, 1980).

The process of analyzing the kinematics and kinetics of human motion from cinematographic techniques presents

some difficulties due to the human error involved in data collection. Such error was introduced in the displacement-time data. Efforts to objectively identify joint centers were carefully controlled through stringent experimental procedures. The tight-fitting racing suits worn by the subjects allowed for accurate identification of body segments as well as reduced movement of the clothing relative to the skin during performance. Following such procedures, the anatomical markings identified in the analysis of data were assumed to be correct.

The validity of anthropometric data in research has often been questioned. Numerous researchers have summarized the estimates of segment lengths and joint center locations relative to anatomical landmarks (Dempster, 1955; 1959). The body segment parameters serve as a good approximation in the absence of better data. Techniques used in the direct measurement of anthropometric data are sometimes not much of an improvement over the values obtained from tables (Winter, 1979). Thus, the use of data obtained from past research is considered to be within the acceptable boundaries of validity. Differences between the data tables and the actual individual subjects were assumed to be negligible.

A number of theoretical limitations were assigned to the study. The majority of these restrictions were associated with a number of assumptions. The first limitation is rather obvious in that the diagonal stride is only one technique of

many employed during the race. Thus one of the main assumptions was therefore that the particular stride analyzed is representative of the subject's normal diagonal stride technique. The effect of fatigue on performance was assumed to be negligible since the filming occurred relatively early in the race. Related to this condition is the assumption that performance of the stride relies heavily on mechanical factors. Thus no physiological or psychological variables were considered.

Finally, differences in kinetic calculations are assumed to be achieved through the quantification of parameters relevant to the diagonal stride. There is support in the literature for statements that technique is important to the diagonal stride (Haberli 1977; Hiltunen, 1978). The parameters examined in this study were considered to be relevant to the proper execution of the diagonal stride.

Definitions

The definitions used in this study were consistent with the terminology that India (1979) employed in his investigation.

Diagonal stride is an exaggerated walking stride. It is a cyclic activity during which the laterally opposed arms and legs move simultaneously forward and backward in the sagittal plane.

Internal mechanical work refers to the work done by
the muscles to move the limb segments through some desired
pattern. It is calculated through the summation of all
energy components of all body segments, yielding a total
energy curve as a function of time.

Kinetic energy is due to the motion of parts of the
body. It can be divided into two components: translational
energy and rotational energy.

Potential energy refers to the energy of the body due
to a change in vertical position.

Center of gravity is the point at which the center of
mass of the entire body may be theoretically represented.
It is calculated by using the relative weights and locations
of the center of mass of the respective body segments.

Take-off is that point where the camber of the kicking
ski is released allowing the center of the ski to spring
away from the snow.

Stride length refers to the total horizontal distance
the body moves per stride. Figure 3 depicts the sequence of
the skiing stride. The movement from T_0 - T_5 constitutes
one stride.

TO position is the point in time at which the pole is
implanted into the ground.

<u>T1 position</u> is the point in time at which the horizontal movement of the support foot stops.

<u>T2 position</u> is the point in time at which both feet come together at the base of support.

<u>T3 position</u> is the point in time at which the last contact of the pole plant pole with the ski surface is made.

<u>T4 position</u> is the point in time at which the last contact of the support foot with the ski surface is made.

<u>T5 position</u> is the point in time at which the opposite pole in phase T_0 is implanted into the snow surface; this phase initiates the next stride.

<u>Pole implantation phase</u> $(T_0 - T_1)$ begins when the skier inserts the ski pole into the snow. The pole implantation phase terminates when the support ski stops and the body begins to rotate over the point of support in preparation for the thrust phase.

<u>Pre-Thrust phase</u> $(T_1 - T_2)$ starts at the point in time when the support ski comes to a rest. The phase terminates when both feet come together at the base of support.

<u>Kick phase</u> $(T_2 - T_4)$ is initiated when both feet come together during the period when the supporting ski is stationary. From this point in time, the trailing ski
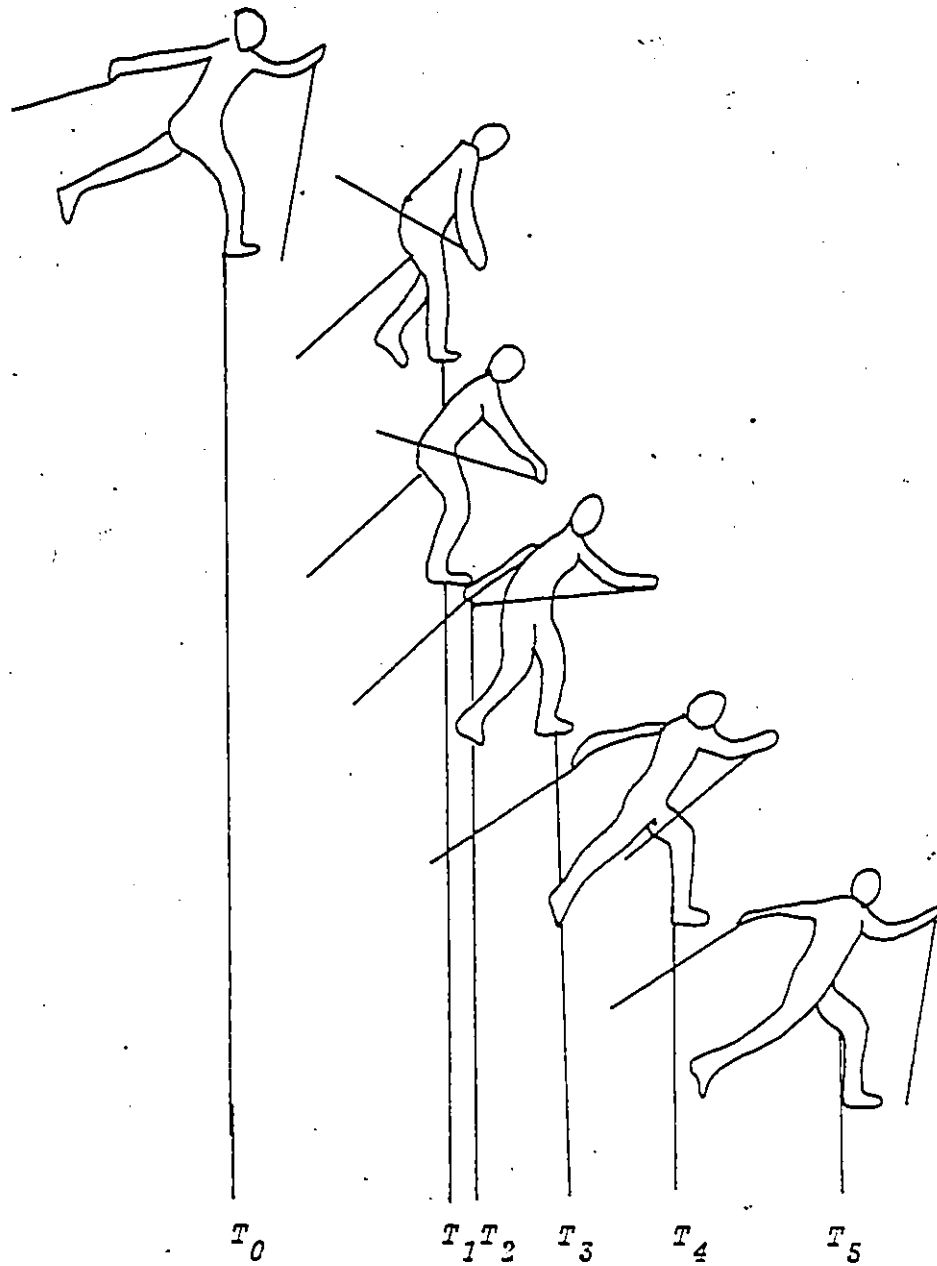
Figure 3: Drawing of a complete diagonal stride.
(Titley,1980)

continues past the support ski in the plane of motion. Termination of this phase occurs when the support ski springs from the track and the thrusting leg becomes fully extended.

Glide phase ($T_4 - T_5$) refers to the portion of the movement cycle characterized by a lack of propulsion. The phase terminates when the pole is inserted into the snow.

Stride rate refers to the rate at which the basic stride is repeated per second (also called cadence).

Positive work is that done during a concentric contraction where the muscle moment acts in the same direction as the angular velocity of the joint.

Negative work is that done during an eccentric contraction where the muscle moment acts in the opposite direction to the angular velocity of the joint.

Movement cycle consists of two strides performed in sequence, one following the other.

Cycle length refers to the horizontal distance the body moves in one movement cycle, or two strides.

Cycle rate refers to the rate at which the movement cycle is repeated per second.

CHAPTER II

REVIEW OF LITERATURE

The mechanical parameters related to female cross-country skiing have been neglected by researchers in the past. The review of literature was divided into four parts. The first three sections comprise an overview of mechanical energy, work, and energy transfers. The final section provides a review of biomechanical studies related to the mechanical parameters of female cross-country skiers.

Mechanical Energy

A total analysis of locomotion requires simultaneous measurements of the mechanical energy levels of each segment of the body as a function of time, along with metabolic data. Methods for collecting metabolic data are well-known, however assumptions related to the calculation of mechanical energy in past studies have lead to discrepancies in the results reported (Elftman, 1939; Cavagna et al 1963, 1964, 1966, 1971; Bresler et al, 1951; Ralston and Lukin, 1969).

The analysis of mechanical energy has been accomplished with the use of two models: one which regards the body as a linked system of segments; and one which views the body

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as a single point mass. Numerous researchers have employed the time-displacement curves of the center of mass to determine the energy changes of the total body (Cavagna et al 1963, 1964, 1966, 1971; Gage 1964; Gersten et al, 1969).

In the earliest studies by Cavagna et al (1963, 1964), an accelerometer was used to calculate the displacement of the trunk in two (1964) and three (1963) planes. The displacement of the center of gravity within the body was calculated from cine analysis. Similarly, Gersten et al (1969) determined the energy used in level walking with the use of a triaxial accelerometer. Such studies however assume accelerometers to be representative of the center of mass and do not allow for the disorientation of the unit due to pelvis tilting during the movement (Caldwell, 1980).

Cavagna and Margaria (1966) and Cavagna et al (1971, 1976, 1977) later attempted to overcome the problems associated with such an assumption through the use of force platforms. Typically, the energy of the body was measured at each step from data obtained from platforms sensitive to vertical and forward components. One study (Cavagna et al, 1964) used two small platforms which may have necessitated gait changes by the subject in order to make contact with the platforms. Larger platforms were used in later studies to correct this problem.

Both the accelerometer and force platform methods are based on the assumption that the trajectory of the body's

center of mass contains the necessary information to calculate the mechanical energy of the body. The error involved in such an assumption is of particular importance in symmetrical movements. In walking or running, for example, reciprocal movements of limbs in opposite directions produce changes in the potential and kinetic energy levels of the segments but may not result in a center of gravity change. The assumption also fails to acknowledge the energy of the limbs, which may have much higher velocities than the trunk (Caldwell, 1980). The error involved in such an assumption was clearly demonstrated in a study by Winter (1979) which showed the energy level of the center of gravity of the body to be lower, and show less change, than the sum of the segmental energies. The average error was shown to be 16.2 percent.

The modern groundwork for the determination of mechanical energy was laid by Fenn (1929) in a study which calculated the kinetic and potential energy values of a sprinter from cine film. Elftman (1939) later modified Fenn's technique and, using both cine film and a force plate, calculated the energy components for leg segments during walking. Although these studies were probably the first to look at segmental energies, both failed to include within segment energy transfers, and in Fenn's case, between segment transfers as well.

The segmental analysis technique for determining the total energy of the body requires the summation of the

energies of each of the body segments at each point in time (Bresler et al, 1951; Ralston and Lukin, 1969; Winter et al, 1976). Various methods have been employed by researchers in an attempt to adequately analyze the energetics of the segments. Bresler and Berry (1951) recognized the energy exchange present within segments in their summation of energy components, but failed to include the energy of the head, arms, and trunk (Winter, 1979). Using transdueers attached to the centers of mass of the leg and trunk segments, Ralston and Lukin (1969) calculated the potential and horizontal translational kinetic energy levels of the trunk as well as the horizontal translational kinetic energy of the leg segments. However the lateral and rotational movements of the lower body were excluded, thus underestimating the energy level of some segments (Winter et al, 1976).

Segmental models used in the analysis of mechanical energy depict the upper body as one segment hinged to a linked lower half. Such a system disregards energy changes due to arm motion.

Norman et al (1976) calculated the total mechanical energy level of the body during treadmill running using a twelve segment model. The equations proposed in their study yielded work values which assumed no energy transfers between or within segments. Winter et al (1976) developed calculations which determined the energy level of each

segment as well as the energy exchanges within segments and
their contributions to the total energy level of the body.
A modified version of these calculations allowed for the
calculation of energy exchanges between and within segments
in a later study by Winter (1979).

Mechanical Work

In the past, mechanical work has been calculated
through the simultaneous measurements of force, weight, and
distance covered (Furusawa et al, 1927), and the application
of force platforms (Fenn, 1929), and accelerometers (Cavagna
et al, 1963, 1964). Although the techniques of film analysis
have also been employed in some earlier studies (Fenn, 1929;
Elftman, 1939, Cavagna et al, 1964), Norman et al (1976)
re-examined the concept of mechanical efficiency in tread-
mill running using cine analysis and subsequently introduced
the term "pseudomechanical" work.

The net mechanical work can be calculated by summing
the internal and external mechanical work done. There exists
however a difference of opinion among researchers as to how
these two components should be calculated. Cotes and Meade
(1960) measured the vertical oscillation of the body's
center of gravity by way of a wire attached to the trunk.
The work done by the body was equal to the vertical lift
work of the trunk per step. Dean (1965) considered the net
energy expenditure of walking to consist of three components;
that due to leg swinging, progressional oscillation of the

body, and the vertical motion of the body. Other researchers have suggested the total external work performed during any activity can be determined from the sum of work for vertical and forward displacements of the center of gravity of the body (Cavagna et al, 1963, 1964). Velocity changes in the forward direction denote a variation in the kinetic energy level, the vertical displacements of the center of gravity indicate changes in the potential energy level. Internal work was considered to be the result of isometric contractions, overcoming muscle viscosity and joint friction, and reciprocal limb movements (Cavagna et al, 1964).

Margaria (1963) first considered internal work to include both positive and negative work values. In an early study by Cavagna et al (1966) an increase in the speed of walking revealed an increase in the work due to velocity changes with a simultaneous decrease in the work done against gravity. It was also suggested that the shift from potential energy to kinetic energy, and vice versa, was most efficient when the two energy changes were of approximately the same magnitude.

Later, using a force platform, Cavagna et al (1971) found almost all the positive work done during the first second of sprint running was accomplished by an increase in the kinetic energy of the body. However, an increase in running velocity resulted in an increase in negative work.

A comparative study conducted by Cavagna et al (1976) measured the work done in the vertical and forward directions while walking and running at various speeds. At lower speeds the vertical work component was found to be larger than the forward work component whereas at higher speeds the opposite was true. The recovery of mechanical energy, in the form of potential-kinetic energy interchange, was found to be minimal during running, resulting in higher external work values.

The ability of the body to optimize its energy consumption during normal gait has been noted by various researchers (Asmussen and Bonde-Petersen, 1974; Inman, 1966). Inman concluded that "...the body will integrate the motion of various segments of the body and control the activities of muscles so that the energy required by each step is minimal". Cavagna et al (1977) later expanded this principle to include all forms of gait and theorized that locomotion is performed at a minimum of energy expenditure through one of two mechanisms: the exchange of potential and kinetic energy, or the storage and release of elastic energy. However, the negative work component was ignored in their calculation of their total work done.

The above studies have all determined total work with the assumption that the center of gravity of the body contains the necessary information for the calculation of external work. This point mass model fails in that while

reciprocal limb movements do not change the center of

mass trajectory, they do require energy expenditure.

Fenn (1929) provided the first detailed analysis of energy

expenditure during locomotion. Summing the increases in the

potential and kinetic energy components for each segment,

Fenn was able to calculate the work done during sprint

running. However, his methods did not account for energy

exchanges and thus resulted in predictably high mechanical

work values. Smith (1975) illustrated the magnitude of

error incurred when the center of mass of the body is used

as a base for the calculation of kinetic energy. His study

suggests that the more complex the motion, the more discrepancy

between the work value calculated and the actual work done,

when the center of mass is used as a reference. Norman et al

(1976) examined the work done in treadmill running using a

segment-by-segment analysis. However, the total work done

was calculated assuming no energy exchange.

Winter (1979) proposed a segmental, 'internal' work

calculation which accounted for both positive and negative

work, energy exchanges within and between segments, and all

potential and kinetic energy components. This value, in

conjuction with Norman and colleagues' (1976) "pseudo-work"

value, allows the calculation of mechanical work done with

three separate assumptions: 1) no energy transfer;

2) between segment transfers only; 3) within and between

segment transfers. Subsequently, the magnitude of the energy

transfers within and between segments can be calculated

(Pierrynowski et al, 1980).

Energy Transfer

Passive energy exchanges within the body segments
and between adjacent body segments are in existence during
locomotion. Elftman (1939) was the first to recognize
the presence of between energy transfers. Energy flows
across the joints were obtained from force plates and
kinematic data. However the transfer of kinetic to po-
tential energy and vice versa was not considered at that time.

The phenomena of within segment energy transfers was
first realized by Cavagna et al (1963). In level walking,
the body's kinetic energy level was found to be transformed
into into the potential energy as the body is raised, and
subsequently transformed back into kinetic energy as the
body falls. The phasic differences in the kinetic and
potential energy levels illustrated the recovery of
mechanical energy was suggested to be up to 65% of the total
energy value (Cavagna, 1963). A later study by Cavagna (1964)
revealed little transfer of energy during running as noted
by the kinetic and potential energy levels, which were rela-
tively in phase. The study neglected rotational kinetic
energy in the calculations. A study of level walking by
Gersten et al (1969) verified the presence of a kinetic-
potential energy exchange mechanism. The sum of the three
separate components, including rotational kinetic energy,

was found to be greater than the total energy value.
However, both Cavagna et al and Gersten et al's work employed
the point mass system.

Most body segments contain all three forms of energy
storage at any point in time during a movement. Winter
et al (1976) calculated the instantaneous energy of each
segment by summing the energy components during each time
interval. These energy values were subsequently summed to
produce the total instantaneous energy of the body. The
authors concluded that during normal gait, the torso acts
as a conservative system interchanging about half of its
potential and kinetic energy changes. In addition, the
thigh was found to conserve approximately 30% of its energy
change through within-segment transfers.

A complete assessment of the energy flow from one
segment to another requires a more detailed analysis, in-
cluding the calculation of joint moments and joint forces
(Elftman, 1939). Quanbury et al (1975) compared instantaneous
power, determined from the derivative of instantaneous
energy, within power flow to the segment via inter-segment
forces as reported by Elftman (1939). The results were found
to be in close agreement, however the methods used by Quanbury
et al provided a simpler, more direct method of determining
power flow across joints and are based on fewer assumptions.

Capozzo et al (1976) identified a significant inter-
change of energy between the swing leg and the total energy

of the body during walking. The accelerating limb was found to subtract about 40% of its energy requirement from the rest of the body. Similarly, Inman (1976) suggested that 60% of the energy needed for forward velocity during walking is generated by the rapid deceleration of the recovery leg at the end of the swing phase.

In a recent study by Winter (1979) a new definition for internal work was proposed which accounted for energy exchanges within and between body segments. When used in conjunction with the equations presented by Norman et al (1976), this work value enables the magnitude of energy transfers within and between segments to be calculated (Pierrynowski et al, 1980).

Cross-Country Skiing

The amount of research performed regarding the mechanisms of propulsion in cross-country skiing has increased in the past few years. The need for additional biomechanical knowledge of cross-country skiing was stressed by Ekstrom (1978). The majority of research concerning this skill is concentrated on the performance of the diagonal stride technique. Of the literature available very little pertains to the mechanics of female cross-country skiing.

The earliest studies in cross-country skiing were performed by European researchers. Carlsen (1975) reported on the propulsive and resistive components involved in the diagonal stride. Results indicated that the thrust of the kicking leg should be short and forceful as it is only the

initial portion of the thrust which significantly affects
the results of the thrust. In addition, since the hip ex-
tensors provide most of the initial thrust, it is suggested
that knee extension should thus follow, and not coincide with,
the extension at the hip. Carlsen further found that skiing
velocity is decreased as a result of friction of the trailing
ski upon contact with the snow. Hence, it was suggested that
delaying the trail leg from touching down would also ensure
proper weight transfer. Finally, Carlsen suggested that the
plant of the pole should not be too far forward as the more
acute poling angle will result in a larger component in the
direction of travel (Martin, 1977).

Haberli (1977) examined selected mechanical parameters
associated with cross-country skiing on a 15% incline. By
attempting to correlate descriptive temporal data with race
finish, Haberli found an increase in stride length to be most
important in increasing the skier's velocity. The stride
length was thought to be partially dependent on the force of
the leg thrust during the thrust phase. An increase in stride
rate also increased the velocity, but not to the same extent
as an increase in stride length. Caldwell (1980) reported
a study by Hiltunen (1978) which echoed Haberli's conclusions.
In a comparison of the temporal characteristics of the diagonal
stride, elite skiers were found to have longer stride lengths
with lower cadence than unskilled skiers.

Waser (1976) investigated the biomechanical performance
traits of over fifty world class male skiers during a fifteen

kilometre race. Results indicated that better skiers had
shorter thrust phases, longer percentages of glide time,
and shorter poling phases. The longer glide phase was found
to be facilitated by positioning the center of gravity
further to the rear during the phase. The angle of the shank
at the beginning of the thrust phase was found to be of im-
portance, the optimal angle being 63 degrees. The optimal
angles for the center of gravity (101') and the trunk (53')
relative to horizonal during this phase was also reported.
Waser concluded that the comparison of the characteristics of
individual skiers with those of world class competitors can
lead to recommendations for improvement in technique
(Martin, 1977).

Solimon (1977) duplicated Waser's (1977) study in an
attempt to confirm the results. As in Waser's study, the
center of gravity during the glide phase was found to be
further to the rear, permitting easier gliding and better
balance. The optimal angle of the center of gravity at
the beginning of the thrust phase was also found to be in
accordance with Waser's findings. In addition, Solimon re-
ported a relationship between stride length and stride rate
as well as between stride length and velocity. Results
suggested the objective of the skier would be to lengthen the
distance per stroke while attempting to slightly decrease or
maintain the repetition of the stroke. Better skeirs were
found to achieve a greater thrust impulse and a greater speed

with a shorter thrust time (India, 1979). Solimon concluded
that there were many different variables which distinguish
higher race finishers from lower ones.

Martin (1977) developed multiple linear regression
models relating selected mechanical parameters of the diagonal
stride to cross-country skiing performance. Results indicated
that a compromise must occur between increasing the distance
and decreasing the time to cover that distance during a par-
ticular phase or the whole stride. Martin suggested that to
increase the skier's velocity, emphasis should be placed on
increasing the stride length as opposed to increasing the
stride rate. Such an increase should occur as a result of in-
creasing the pole phase and thrust phase distances, which
is in discordance with previous studies (Waser, 1976; Solimon.
1977).

India (1979) examined the temporal and kinematic data
of twenty-two world class female skiers. The thrust phase
was found to be responsible for increasing the velocity of
the skier to a maximum during the glide phase. The position
of the trunk at the beginning of the thrust phase was found
to be of importance in allowing additional force to be
transmitted through the ski pole at the termination of the
pole phase. Flexion of the trunk before the thrust phase
allows the skier to press down upon the support ski, thus
initiating the thrust forward. India concluded that a smaller
angle at the trunk complements the shoulder-arm complex during

poling, compresses the ski for an effective pole thrust, and is there fore essential to an effective performance (Caldwell, 1980).

Marino et al (1979) investigated the diagonal stride techniques of female cross-country skiers. The better skiers exhibited a greater forward lean and fuller hip-ankle extension during the kick phase. The mean angles at the start of the kick phase for the trunk and the shank were 54.60% and 83.20% respectively. These values were in contrast to those reported in a previous study by India (1977). In addition, the glide phase was found to consist of 17.2% of the total stride time, which is in disagreement with results reported by Waser (1976).

The major factor causing differences in velocities between skilled and average skilled skiers was suggested to be the distance attained per stoke, of the stride length (Dillman et al, 1980). It was suggested that the difference in distance attained during the poling phase best distinguished the better skiers from the poorer ones.

Titley (1980) examined the kinematic parameters involved in the diagonal stride. The vertical displacement of the center of gravity was found to exhibit a distinct temporal pattern. According to Carlsen (1975) however, good skiers demonstrate little or no up and down movement. The mean stride length was reported to be 2.41 meters, which is comparable to that reported in previous studies (Dillman et al, 1980; Komi, 1980).

Caldwell et al (1979) investigated five male cross-country world class skiers for differences in mechanical work output and energy transfer. Results showed a substantial amount of energy exchange between the segments as illustrated by the oscillations of the energy curves of the arms and legs. A comparison of the energy components showed some of the transfer of energy within segments, however these transfers were not complete. Overall, a great variety in work output was found for the five skiers.

Two distinct levels of cross-country skiers were studied in a mechanical work and energy transfer analysis by Caldwell (1980). Ten world class skiers and eight novices were filmed performing the diagonal stride on level terrain. Results showed a greater exchange of potential and kinetic energy by the skilled skiers, indicating a better use of gravitational force to attain higher transfers within the segments. Caldwell suggested that novice skiers tended to use muscular energy to perform a process that could have been performed by gravity. Such action also abbreviated the kick, resulting in a shorter gliding phase and shortened stride length. The mechanical task cost of the skill did not differ significantly between the elite and novice skiers.

Summary

Research investigations have provided data on the mechanical aspects of various techniques in cross-country skiing.

The diagonal stride has been extensively studied, securing a solid base of data. Numerous conclusions may be drawn from the research reviewed.

As revealed in the literature, the calculation of mechanical work necessitates the use of a formula which accounts for energy exchanges within and between segments as well as both positive and negative work. The transfer of energy can be determined via cine analysis using equations proposed by Norman et al (1976) and Winter (1979). A linked segment model provided a better estimate of the body's total mechanical energy and was therefore employed rather than a point mass system (Smith, 1975).

Various descriptive studies have attempted to correlate good technique with kinematic variables. With the exception of Caldwell (1980), few have described the mechanical causes of the variables. Research has indicated skilled skiers increase their stride length. In terms of mechanical work output, novice skiers tend to use mechanical energy to perform skills, or parts of a skill, which could be assisted by gravity.

Although the data on a diagonal stride is extensive, few studies of the mechanical parameters of female cross-country skiers have been undertaken. Further research is needed to understand the mechanics of skiing. A technique of research which allows for complete mechanical analysis of the diagonal stride is the mechanical energy and work output calculation.

CHAPTER III

METHODS

The purpose of this study was to determine the internal mechanical work output and energy transfers of elite and skilled female cross-country skiers. The skill studied was the diagonal stride technique.

High speed cinematography in conjunction with a computerized analysis of data was utilized in an attempt to accurately quantify the kinematic and kinetic variables related to the technique. A detailed description of the specific methods employed follows.

Subjects

The sample consisted of three international level female cross-country skiers and three provincial level skiers. The race in which they were filmed was the 1979 North American Cross-Country Ski Championships.

Each skier was wearing typically tight-fitting racing attire. Thus, subject preparation was minimal since such apparel allowed anatomical markings and body segments to be easily distinguished. Additional joint markers were not employed so as not to interfere with the athlete's performance during the competion.

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Filming Area

The filming area was located approximately 150 meters
from the start of a 10 kilometer race. This area was dis-
tinguished by a single racing track with a slight uphill
grade of one to two percent. Although this site ensured
that all racers performed the diagonal stride technique,
such a grade may have affected the energy level of the skiers.
The skiers were identified by numbers attached to their
clothing.

Filming Procedure

Various requirements as noted in the review of literature
were satisfied in an effort to decrease and/or eliminate
sources of error.

Each racer was filmed once with a Locam sixteen millimeter
camera operating at one hundred (100) frames per second. The
filming position was stationary at a height of approximately
1.0 meters since movement of the camera would have resulted in
measurement error. The camera was located perpendicular to
the racing track so that a side view of the movement was
recorded. The camera was placed far enough from the track to
ensure a suitable image size on the film, and thus reduced
perspective error in data collection.

The camera was activated prior to the appearance of the
racer in the filming area. Such a practice allowed enough time
for the camera to attain the designated film speed.

A large wooden dowling with distinctive markings spaced
one meter apart was filmed prior to the onset of the race.
It was essential to photograph an object of known length in
the plane of motion to enable the conversion of image distance
to real life distance. Such a procedure required the use of
a 'multiplier' value. Since the real life size was know (one
meter) the multiplier was determined by the following formula:

multiplier = life size/projected size

By following stringent filming procedures, accurate data
was recorded. The accuracy of conclusions drawn from kinematic
and kinetic studies of human motion depends largely upon the
accuracy of body markers, and displacement, velocity, and
acceleration measurements.

Film Analysis Procedures

The basis of film analysis was the collection of data
values through the digitizing of appropriate segmental end-
points. Such a method was used in this study. The film
analysis system used was the Numonics electronic graphic
calculator. Fifteen segmental endpoints were included in the
analysis. The position of each segment endpoint was recorded
based on the cartesian coordiante system and assigned X and
Y values.

Kinematic and kinetic studies required the positions of
various limb segments as a function of time. The positions
were calculated in the form of linear or angular displacements.

Timing Parameters

The time factor was calculated with the aid of a light emitting diode device located in the camera. The device, driven by a quartz crystal oscillator, produced exposure marks at accurate .01 second intervals along the film's edge. By counting the number of exposure marks and frames within a length of film, the frame rate was determined. Subsequently the time per frame was calculated. The following equations were used to calculate the film speed and time per frame, respectively.

$$\text{Film speed} = \frac{\text{\# of frames}}{\text{\# of exposures}} \times \frac{100 \text{ exposures}}{\text{second}}$$

$$\text{Time/Frame} = \frac{1}{\text{film speed}}$$

Calculation of Linear Displacement

The determination of the X and Y coordinates at any time period is the basis of calculation of linear displacement. The projection of the image by the Vanguard M-16c projector allows the researcher to determine their location by moving a mechanical cartesian coordinate system until the stylus lies over the desired anatomical landmark. Between two positions of any landmark, linear displacement can be calculated. The linear displacement values for all segmental endpoints in this study were computed using the following formula:

$$\text{Horizontal Linear displacement} = (X_1 - X_2) \times \text{multiplier}$$

$$\text{Vertical Linear displacement} = (Y_1 - Y_2) \times \text{multiplier}$$

Calculation of Absolute Angles

Angular measurements were computed through the manipulation of a Fortran computer program. The determination of the absolute angles succeeded the recording of the positions of the segmental endpoints relative to the X-Y axis. The equation used for the computation of the angles follows:

$$\theta = ARCOS \frac{(b+c-a)}{2(bxc)}$$

where a, b, and c represent adjacent sides.

Center of Gravity

The center of gravity for the body was determined for each frame. The segmental method was used to calculate the location of the center of gravity. Dempter's (1955) segmental weights and the center of segmental mass percentages found by Clauser et al (1966) were used to calculate the moments about the X-Y coordinate axes. The spatial coordinates for the segmental endpoints were used in the Fortran program to compute the center of gravity.

The mass of each segment was also calculated. This parameter was necessary for the determination of the kinetic energy of each segment. The individual segmental masses were calculated by employing the following formula:

$$M_i = Wt_b \times CGW_i$$

where Wt_b is equal to the mass of the body

and

CGW_i is the percent of the total body weight

for

the ith segment.

Calculation of Segmental Moments of Inertia

The determination of segmental kinetic energies required the calculation of the moments of inertia for individual limbs. The value of the moment of inertia depends on the point about which the rotation is taking place and is a minimum when the rotation occurs about its center of mass. The moment of inertia for each segment was calculated with the use of Dempster's (1955) data on the radius of gyration. The formula employed for the determination of the ith segment follows:

$$I_i = M_i \times (L_i \times R_i)^2$$

where M_i = mass of segment i

L_i = length of segment i

R_i = radius of gyration of the ith segment expressed as a proportion of the length.

Calculation of Performance Parameters

Through the review of literature, the following body movement parameters were found to be of prime importance for

the analysis of the diagonal stride (Waser, 1976; Dillman, 1979; Carlsen, 1975);

    1. stride length

    2. stride rate

    3. percent of total time spent in each phase

The stride length was calculated by determining the horizontal distance the body moved from take-off of one ski to take-off of the opposite ski. The stride rate refers to the rate at which the cycle of movement was repeated per second. The formula used in the calculation of the stride rate is expressed below in strides per second.

$$SR = \frac{1 \text{ stride}}{\text{stride time (sec)}}$$

Calculation of Stride Phase Parameters

The following phase parameters were examined. The calculations and times were determined using specific, distinguishing times at which certain events occurred throughout the stride.

    1. Pole implantation phase

    2. Kick Phase (thrust)

    3. Glide Phase

Kinetic Energy

The kinetic energy of each segment was determined with the aid of a computer program. The fundamental expression

the kinetic energy was partitioned into two categories: translational and rotational kinetic energy. The formulae for these separate energies are listed below. The sum of these two formulae produced the total kinetic energy for one segment.

$$KE = \tfrac{1}{2}(M_i(U_i{}^2 + V_i{}^2))$$ translational

$$RKE = \tfrac{1}{2}I_iW_i{}^2$$ rotational

where: M = mass of segment

  U = horizontal velocity component

  V = vertical velocity component

  I = rotational moment of inertia

  W = rotational velocity

  i = ith segment

The direction of the velocities is not important since velocity squared is always positive. Although partitioned for the purpose of calculating kinetic energy, the term used in the results section of this manuscript (KE), refers to the combined kinetic energy, since RKE was minimal.

Potential Energy

Potential energy values for each segment were calculated. The surface of the ski was used as the ground reference datum. The formula below was employed to determine the potential energy values for each segment at any point in time.

$$PE = MGH$$ potential

where: M = mass of segment

G = acceleration due to gravity

H = height of center of segment's mass

Total Energy

The energy of the body exists in three forms. The total energy of the body (E) is equal to the summation of these three energy values. Thus, the following formula was used to calculate the total body energy at any given point in time.

$$E = PE + KE + RKE \quad \text{or}$$

$$E = MGH + \tfrac{1}{2}M(u^2 + v^2) + \tfrac{1}{2}Iw^2$$

It is possible for the body to exchange energy within itself and still maintain a constant total energy. The methods used for determining energy exchanges, through the calculation of mechanical work values, have been discussed extensively in the introduction portion of this paper.

Analysis of Data

The analysis of kinematic and kinetic parameters of human movement derived from cinematographic techniques presents some difficulties due to the experimental error inherent in the collection of displacement-time data. Although the removal of 'noise' can be accomplished using several smoothing techniques. A cubic spline curve fitting procedure was prior to the comparative analysis of the data. This technique, which is a modification of the polynomial

technique, was used to smooth vertical and horizontal displacement values.

A comparative analysis using independent t-tests was made between mechanical work output values and total energy levels of the elite versus the skilled skiers. Individual segmental energy levels were also analyzed using t-tests. The magnitudes of energy exchange for both groups were then compared to determine where differences in performance occurred.

CHAPTER IV

RESULTS

The purpose of this study was to determine the internal mechanical work output and energy transfers of elite and skilled female cross-country skiers. The skill studied was the diagonal stride technique.

Three elite international level skiers and three provincial level skiers were filmed and analy ed according to the methods and prodedures described in previous chapters. Within the body of this text, skiers referred to as subjects 1, 2, 3, were of international or elite caliber, while subjects 4, 5, 6, were the provincial level skiers. The mean weight was 55.9 kg. for the elite skiers; while the skilled skiers' mean weight was 54.54 kg. (Table 1). Due to the similarities in the kinematic data between the two groups, it was doubtful that physical factors affected the mass component of the potential energy calculations enough to be responsible for any differences in the reported results.

Kinematic Data

Results from kinematic analysis calculated by Marino et al including step length, step time, step race, and horizontal velocity are presented in Table 2. The mean

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TABLE 1

SKIER WEIGHT

S		Weight (kg)
1		54.54
2		58.63
3		54.54
$\overline{X}$		55.90
SD		2.36
4		56.81
5		47.72
6		59.09
$\overline{X}$		54.54
SD		6.01

TABLE 2

SKIER KINEMATICS

s	step length (m)	step time (sec)	step rate (step/min)	velocity (m/sec)
1	2.16	.51	1.98	4.28
2	2.07	.50	2.02	4.18
3	2.29	.53	1.87	4.28
$\bar{X}$	2.17	.51	1.95	4.24
SD	.11	.01	.07	.05
4	1.76	.53	1.90	3.34
5	1.75	.52	1.94	3.40
6	1.74	.53	1.90	3.31
$\bar{X}$	1.75	.52	1.91	3.35
SD	.01	.005	.02	.04

(Marino et al, 1980)

horizontal velocity of the elite skiers was 4.25 +/- .058 m/sec, 27% higher than that of the skilled skiers (3.35 +/- .045 m/sec). The mean step length of the expert skiers (2.17 +/- .109 m.) was 24% longer than that of the lesser skilled skiers (1.75 +/- .01 m.). The elite skiers took approximately the same amount of time to complete this longer stride, with a mean step time of .513 +/- .014 seconds, compared to .526 +/- .005 seconds for the skilled skiers. The skiers were found to have similar step rates. Elite skiers showed a mean step rate of 1.95 +/- .078 steps per minute compared to 1.91 +/- .023 steps per minute for the skilled skiers.

Horizontal velocity differences seen in the elite and skilled groups compared favourably with previously reported studies (Martin, 1979; Caldwell, 1980). The substantially higher step length demonstrated by the elite skiers indicated that the increased velocity occurred as a result of increased step length. Since little difference was noted in the cadence, and step rate, it was assumed the most important factor in increasing horizontal velocity amongst female skiers was an increase in step length. Earlier studies by Martin (1979) and Marino et al (1980) agree with this finding. Caldwell (1980) attributed an 18% increase in velocity by the elite skiers to a 13% longer step length coupled with a 7% lower step rate.

Mechanical Work

Three mechanical work values were calculated and are listed in Table 3. Of these three values, the Wwb value

TABLE 3

MECHANICAL WORK OUTPUT

S	WN (joules)	WW (joules)	WWB (joules)	Mechanical Task Cost (j/kg-m)
1	1154.70	612.54	522.79	4.43
2	1123.40	758.13	547.51	4.51
3	833.27	664.95	465.00	3.72
$\overline{X}$	1037.12	678.54	511.77	4.22
SD	177.23	73.74	42.34	.43
4	982.07	787.30	619.98	6.20
5	396.12	313.89	254.95	3.05
6	638.17	539.91	453.38	4.40
$\overline{X}$	672.12	547.03	442.76	4.55
SD	294.44	236.78	182.73	1.58

most closely approximates the true internal mechanical work output. This value assumes both within and between energy transfers.

The Wn value, which assumes no energy transfers, was 54% higher for the experts. This increase can be accounted for by the 27% velocity increase also demonstrated by the elite skiers. The Ww value of the elite skiers exceeded that of the skilled skiers by 24%, while the Wwb value was 15.6% greater. It was doubtful that the mass value incorporated in the work equations produced such variance since little difference existed between the groups. Statistical analysis showed none of the work values ot be significantly different between the groups.

The mechanical task cost was calculated to determine the amount of work performed per kilogram of body mass per meter travelled. No significant difference was found for the mechanical task cost between groups. The values obtained were much higher than those reported by Caldwell (1980) and Winter (1979). The calculation of the mechanical task cost required the Wwb value to be divided by the weight and step length of the skier. Both the step rate and velocity values were considerably lower for the females in this study compared to the male subjects in the previous studies. This fact, coupled with higher Wwb values, would account for the differing values of this study and earlier experiments.

Energy Levels

From the motions and masses of the segments, potential
and kinetic energy levels were calculated. Skiers 1 and 6
were chosen for analysis since they displayed the highest and
lowest velocities, and these components have the most effect
on the energy calculations. Due to the quantity of data, the
energy curves of the swing shank and kicking shank of the skiers
displaying the highest and lowest velocities were compared.
These energy curves are plotted in Figures 4 to 6. Vertical
lines in the curves denote the beginning of the glide, pole
implantation, and thrust phases.

The potential energy curves of the swing shank for both
skiers are plotted in Figure 4. Both skiers demonstrate an
increase in potential energy over the glide phase. Assuming
the masses of the skiers' legs did not significantly vary, the
higher PE level attained by the elite skier would be due to
a higher leg kick. The skilled skier terminated the kicking
action prematurely, resulting in a shorter gliding phase
(Appendix 1). By not kicking as high, the skilled skier would
have had less PE to begin the recovery phase. The kinetic
energies of the swing shank, plotted in Figure 5, depict a
steady increace in KE over the stride, while the skilled skier
showed more fluctuations in the curve. Since kinetic energy
is influenced most by velocity, the elite skier would appear
to have maintained a higher velocity over a longer period of
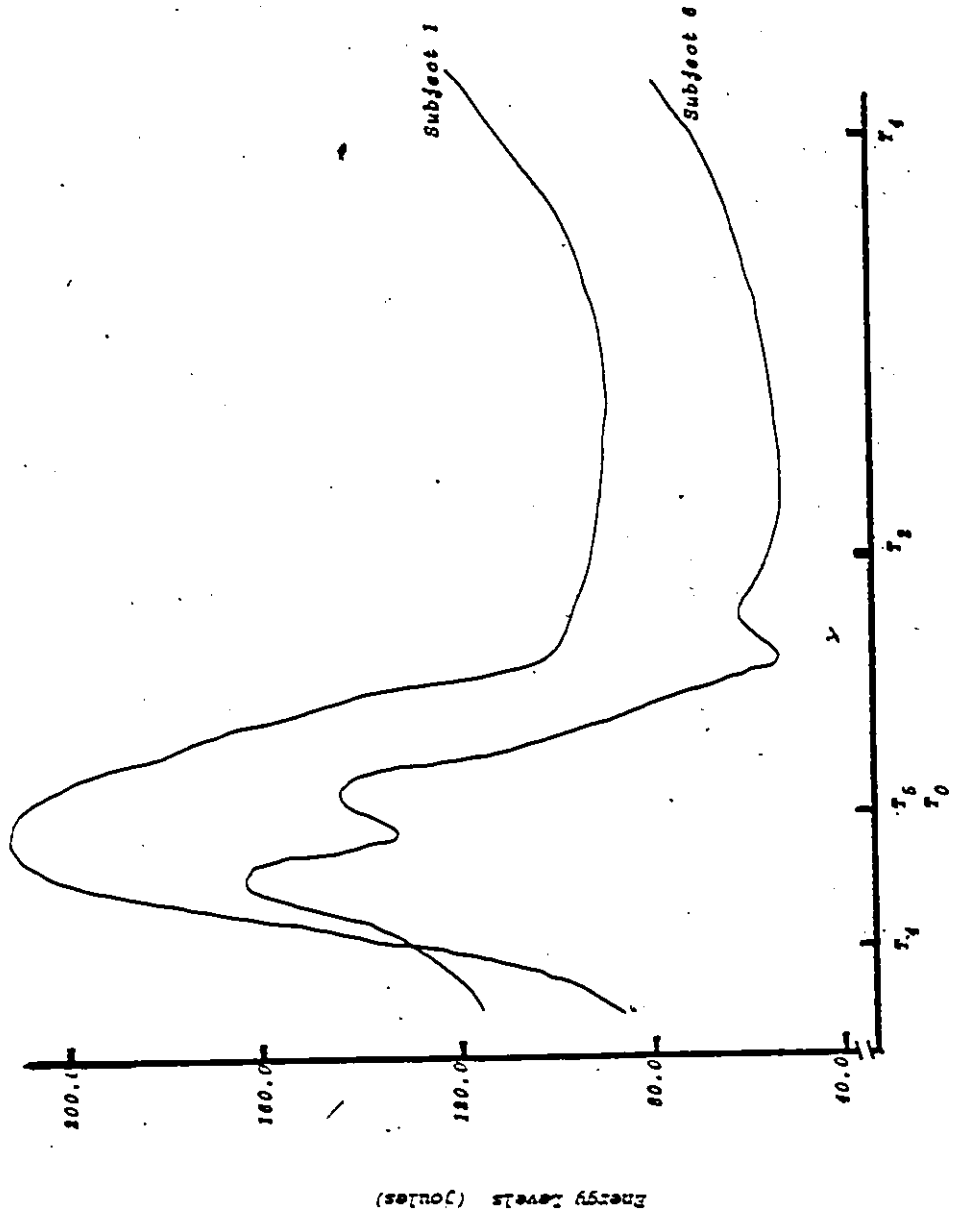time. The point in the curve of the elite skier where the

Figure 4: Potential energy curves of the swing shank for Subject 1 and Subject 6.
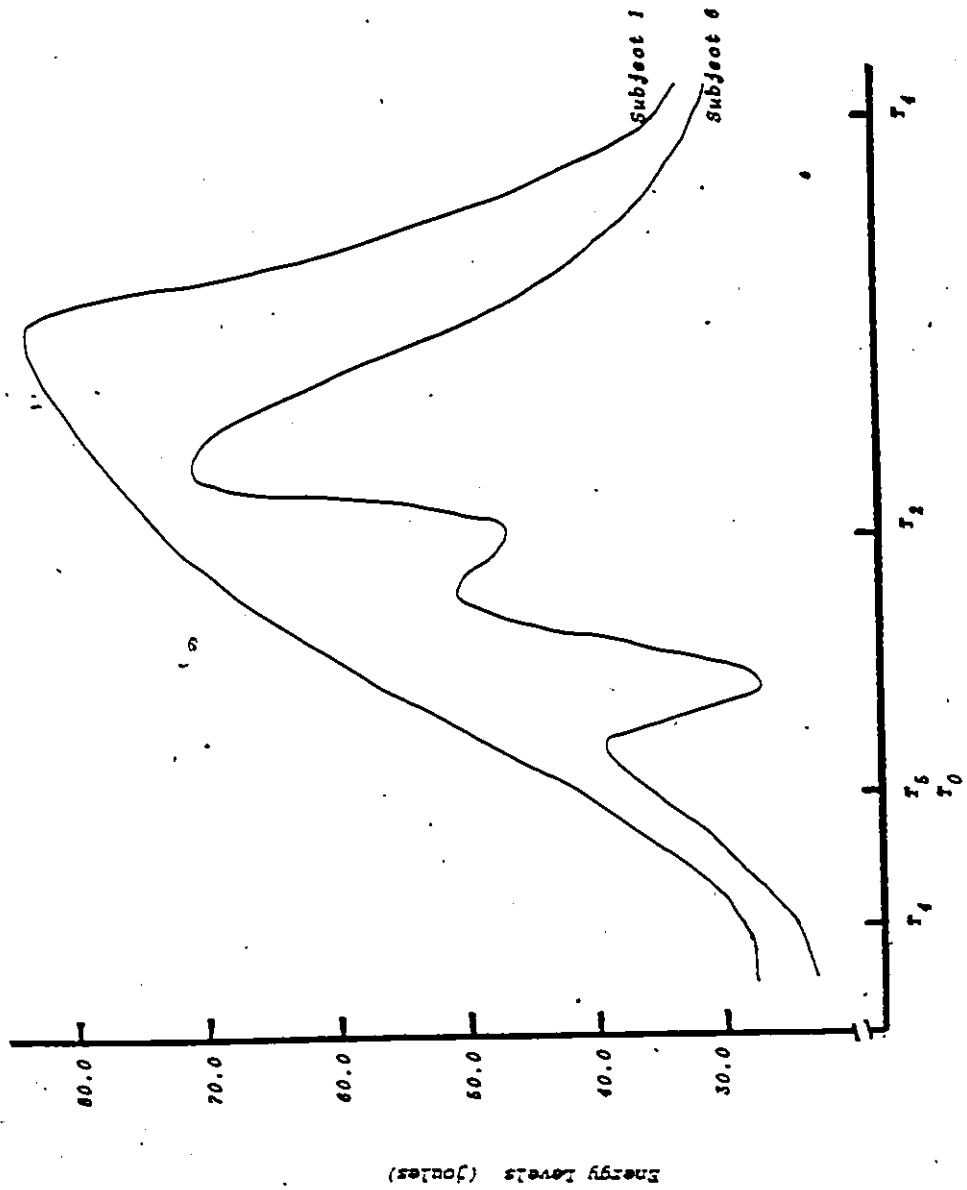
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Figure 5: Kinetic energy curves of the swing shank for Subject 1 and Subject 6.

kinetic energy begins to descend identifies the end of the pole

implantation phase and the onset of the kick thrust. Skier 1

was able to prolong the pole implantation phase due to the

higher leg kick which generated more potential energy. The

high kinetic energy at the end of the recovery phase demon-

strated by the elite skier, is indicative of peak angular

velocity of the swinging shank occurring just prior to the

kick thrust. The kinetic energy curve for the skilled skier

displays peak velocities occurring at different phases of

recovery, with the highest velocities occurring well before

the end of the swing forward. These findings are similar

to those of Caldwell (1980), who suggested that elite skiers

used the force of gravity to initiate the recovery phase while

less skilled skiers actively initiated the forward recovery

phase.

Figures 6 and 7 show the kinetic and potential energy

levels of the kicking shank for both skiers. The ski

of the kicking leg glides along the snow in the first part

of the step, decreasing in speed until the beginning of the

kick thrust. At this point, the level of kinetic energy begins

to increase (Fig. 7). Solimon (1977) found better skiers to

have quicker leg kicks, a finding supported in this study.

Figure 5 shows the kinetic energy of the skilled skier's swing

shank decreasing at the .32 second mark. However, the increaee

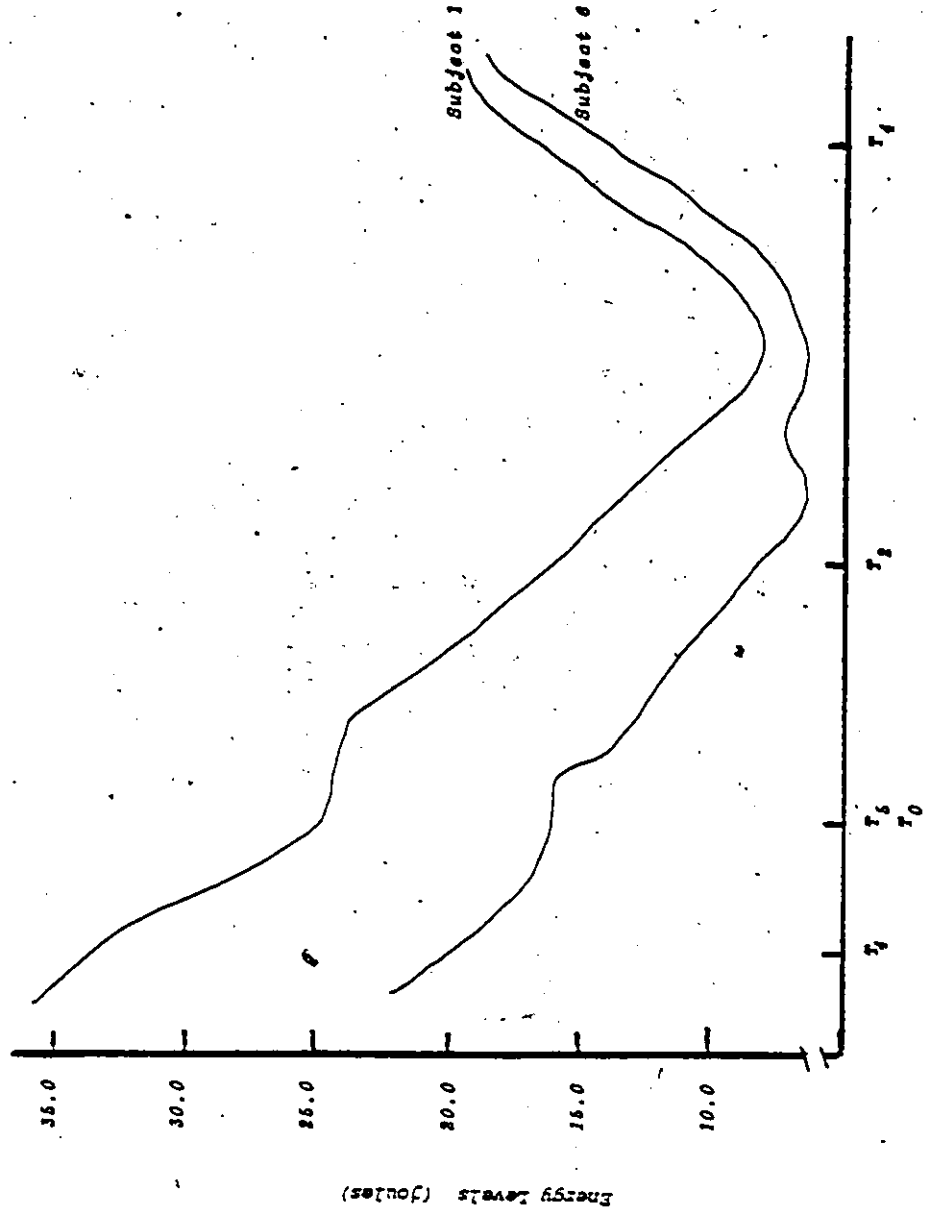in kinetic energy of the kicking shank, marking the onset of

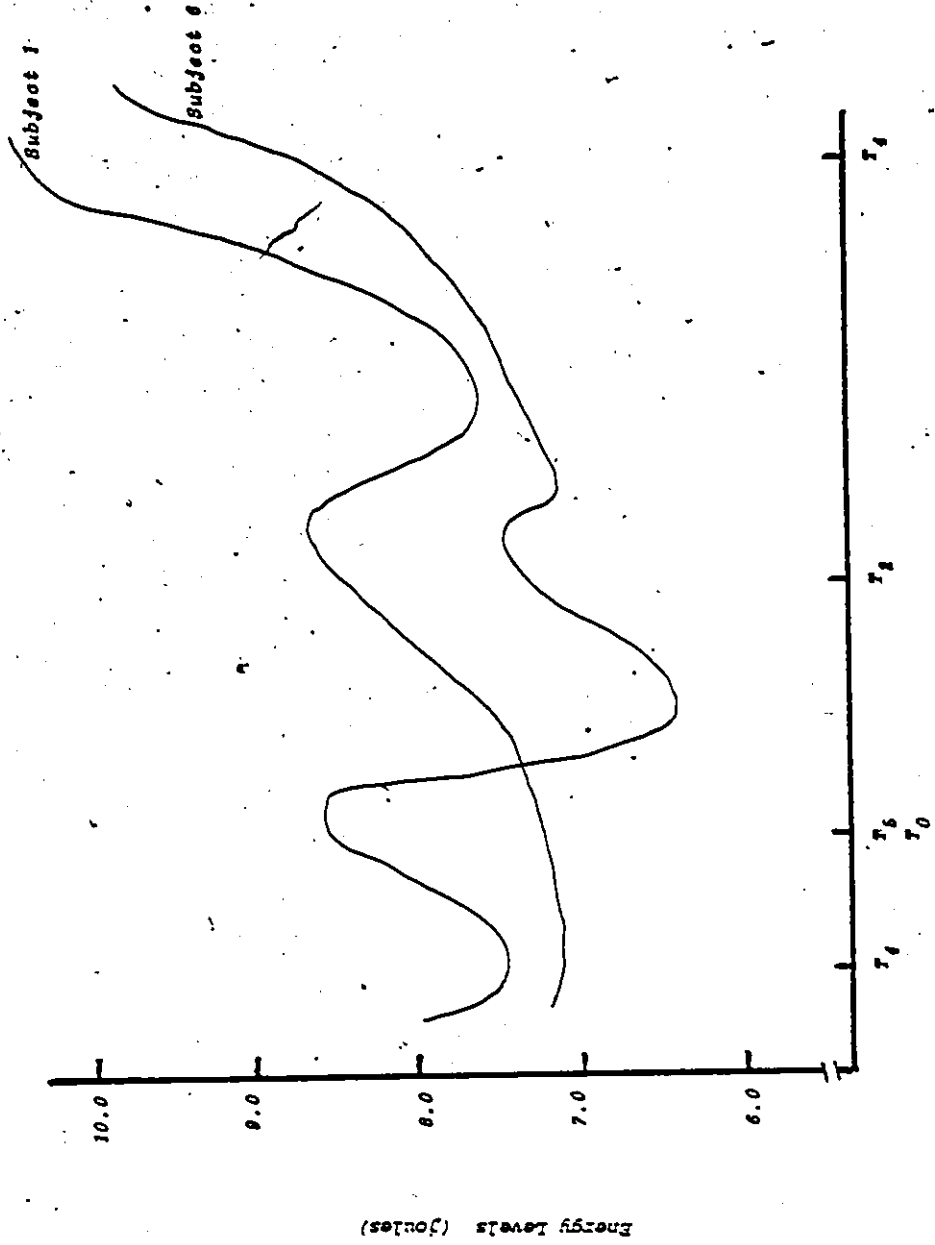Figure 6: Kinetic energy curves of the kick shank for Subject 1 and Subject 6.

Figure 7: Potential energy curves of the kick shank for Subject 1 and Subject 6.

the thrust, does not begin until the .36 second mark. The
energy curves for the elite skier, however, coincide almost
perfectly, indicating a quicker leg kick.

Both skiers demonstrated an increase in potential energy
of the kicking shank over the kick phase. The slope of the
line in Figure 7 again displays the quicker kick exhibited
by the elite skier. During the pole implantation phase, both
skiers displayed an increase and subsequent decrease in po-
tential energy. This phenomena may be the result of flexing
at the knee in preparation for the kick thrust, an action which
would lower the center of mass of the shank, and thereby de-
crease the potential energy level.

Energy Transfers

A high amount of energy transfer between and within
segments results in metabolic energy being conserved, and
should thus indicate superior technique. Table 4 lists the
energy transferred within and between segments in joules as
well as a percent of Wn, work done assuming no transfer of
energy. The elite skiers transferred 77% more energy within
segments (33.18 +/- 13.43) than the skilled skiers (18.66
+/- 2.86). The mean percent between segment transfer for the
elite group was 48% higher than the skilled (18.85% compared
to 12.71%). The total amount of energy transferred for the
elite group was significantly higher (by 66%) than that of the
skilled skiers.

TABLE 4

ACTUAL ENERGY TRANSFER VALUES AND
ENERGY TRANSFERS AS A PERCENT OF
WN

S	Tw (joules)	Tb (joules)	Twb (joules)	%Tw	%Tb	%Twb
1	542.16	89.75	631.90	46.95	7.77	54.72
2	365.25	210.61	575.86	32.50	18.75	51.25
3	167.31	199.95	367.25	20.10	30.06	50.16
$\overline{X}$	358.24	166.77	525.00	33.18	18.86	52.04
SD	187.52	66.91	139.46	13.43	11.14	2.38
4	194.77	95.34	290.11	19.83	9.70	29.54
5	82.23	58.94	141.17	20.76	14.87	35.63
6	98.25	86.53	184.80	15.40	13.56	28.95
$\overline{X}$	125.08	80.27	205.36	18.66	12.71	31.37
SD	60.87	18.99	205.36	18.66	12.71	31.37

The within energy transfer values of the present study were similar to those reported by Pierrynowski et al (1980) in a study on treadmill walking. Caldwell (1980) reported substantially higher within segment transfer values, reasoning that the differences in velocities resulted in the differing PE-KE exchanges. It is likely then that the lower velocity and mass values of the females in this study accounts for the higher percentage of within segment transfers. The velocity of female skiers may more closely approximate the velocities of males when walking than those of males when skiing; and would therefore produce PE-KE transfers similar to those of walking males.

Individual Segmental Transfers

Instantaneous energy values were determined for each limb segment over the step time. While it is possible to calculate within segment transfers, film analysis does not allow the calculation of individual between segment transfers. Tables 5 and 6 contain individual within body segment transfers, partitioned into swing and kick/push segments. The values listed are the amounts transferred as a percentage of the pseudowork (Wn) done by that segment.

Within segment transfers were calculated by summing the differences between the total energy curve and the observed mechanical work output for that segment at each point in time. Caldwell (1980) identified the swing foot, kicking foot, and

TABLE 5

INDIVIDUAL WITHIN BODY SEGMENT TRANSFERS
FOR THE SWING SEGMENTS (JOULES)

S	FOOT	SHANK	THIGH	FOREARM	UPPERARM	TRUNK
1	8.06	19.70	7.90	29.77	38.80	6.92
2	2.80	7.73	12.71	4.73	30.90	30.92
3	5.34	16.42	12.60	36.00	41.67	7.72
$\overline{X}$	5.40	14.61	11.07	23.50	37.12	15.12
SD	2.63	6.18	2.74	16.55	5.57	13.63
4	7.70	9.98	15.13	32.41	36.90	10.56
5	8.00	23.49	11.17	31.73	31.07	23.40
6	8.90	14.63	7.72	33.99	37.35	34.14
$\overline{X}$	8.20	16.03	11.34	32.71	35.10	22.70
SD	.62	6.86	3.70	1.15	3.50	11.80

TABLE 6

INDIVIDUAL WITHIN BODY SEGMENT TRANSFERS

FOR THE KICK/PUSH SEGMENTS (JOULES)

S	FOOT	SHANK	THIGH	FOREARM	UPPERARM
1	40.80	44.44	47.78	17.68	28.15
2	13.17	19.96	16.94	19.89	19.90
3	30.80	39.80	39.70	11.53	31.53
$\overline{X}$	28.25	34.73	34.80	16.36	26.52
SD	13.98	13.00	15.99	4.33	5.98
4	32.18	36.54	10.28	27.06	35.93
5	31.52	31.15	35.75	14.68	14.37
6	23.90	25.35	32.19	.55	4.80
$\overline{X}$	29.20	31.01	26.07	14.09	18.36
SD	4.60	5.59	13.79	13.26	15.94

kicking shank to be the most distinguishing segments. However, both the swing foot and kicking foot transfers of the skilled female skiers were just slightly below those of the elite skiers. The mean kicking shank transfers of the elite skiers were 12% higher than that of the skilled skiers.

No significant differences were found for any segment in comparing within segment transfers between the two groups. The higher total within segment trasfers found in the elite skiers were the result of an overall higher within segment transfer. Although there were no significantly distinguishing segments accounting for the higher transfers, the kicking thigh and pushing upperarm appear to have played parts in the exchange of potential and kinetic energy. The elite skiers' kicking thigh transfers were 33% higher than that of the skilled skiers.

CHAPTER V

DISCUSSION

The purpose of this study was to determine the internal mechanical work output and energy transfers of elite and skilled female cross-country skiers. The skill studied was the diagonal stride technique.

The elite skiers were found to ski at a higher velocity than the less skilled skiers. In an attempt to determine the cause of the velocity defferences, mechanical work output and energy transfers were calculated. The elite skiers exhibited a significantly higher total energy transfer. However, no statistically significant differences were found between the subject groups for within segment transfers. The total within and between segment transfers were greater for the elite skiers by 77% and 48% respectively, although they were not significant at less than the .05 level.

The higher velocities achieved by the elite skiers may be the result of a longer stride length (Solimon, 1977; Hiltunen, 1978). However, Caldwell (1980) suggested the velocity differences of elite skiers may in part be due to a greater potential-kinetic energy exchange. Caldwell found elite skiers made better use of gravitational force to

accelerate and decelerate the limbs, as evidenced by the high transfers. In accordance with this theory, the elite skiers exhibited 77% higher within segment energy transfers. The elite skiers attained a larger potential energy value during the glide phase, (Fig. 4), resulting from a higher leg kick. This higher PE value would have generated more kinetic energy to be used in recovery, as evidenced in Fig. 5. This would account for higher within segment transfer values. Lower potential energy levels exhibited by the skilled skiers (Fig. 4) indicate the active initiation of the recovery phase. A higher potential energy value, a longer glide distance, and a larger velocity value, give evidence of a better use of gravitational force in accelerating and decelerating the limb.

Caldwell (1980) further suggested that any metabolic energy saved by the elite skiers in allowing gravity to assist movement which could be performed solely by muscular work, may be used elsewhere in the skiing motion, or result in an overall metabolic saving. By actively initiating forward recovery, rather than allowing gravity to do it more slowly, the skilled skiers would have had to rely on a greater amount of muscular force than the elite skiers. Harkins (1978) reported lower metabolic expenditures for elite skiers at a given velocity. Examination of the swing shank may provide information as to the cause of lower

metabolic expenditures by elite skiers (Fig. 5). The elite skier displayed a high peak kinetic energy level, indicative of high velocities, at the end of the recovery phase. Assuming a pendulum-like motion to be present, the skilled skiers would have been required to utilize muscular energy to attain these peaks throughout the recovery phase. This use of muscular energy to actively initiate the recovery phase, would result in a higher metabolic expenditure for the skilled skiers. Fluctuations in the potential energy curve, (Fig. 4) would also indicate a jerky motion, as opposed to the smoother movement of the elite skiers.

Little difference exists between the groups in the amount of time spent during each phase. However, there appear to be substantial differences in the amount of distance covered during each phase. Earlier research has suggested that to increase stride length, a skier must increase the distance covered during the pole plant and thrust phases (Martin, 1979). Data for this research indicates little variation exists between the groups in the distance covered in the pole implantation phase. The elite skiers covered .26 meters, or 9% more of the total distance, than the skilled skiers in the glide phase. The kinetic energy curves of the support ski, illustrated in Fig. 5, suggest that the higher velocities achieved in the glide phase occur as a result of the higher kinetic energy value achieved during the thrust phase.

Contrary to expectations, the skilled skiers covered a greater percentage of total distance during the thrust phase than did the elite skiers, 54.6% compared to 46.6%. Solimon reported that better skiers achieved longer stride lengths through shortened thrust time and greater impulse. However, the energy curves of the swing and kick thighs (Figures 8-12) illustrated a greater impulse on the part of the elite skiers. Figure 12 clearly demonstrates a more forceful thrust by the elite skier during the kick phase. Little difference existed between skiers in the kinetic energy curves of the kick shank, the adjacent segment. Thus the greater percentage of total distance covered during the thrust phase by the skilled skiers must be the result of a shorter thrust phase; .95 seconds compared to 1.01 seconds.

The use of energy transfers by the elite skiers, may have contributed to a lower metabolic rate, and therefore a higher rate of mechanical efficiency. Whipp et al (1969) suggested that to obtain an accurate measurement of efficiency, it was necessary to know 1) the total energy utilization and 2) the total work performed by a subject. A differentation was made between mechanical efficiency and motor efficiency. Mechanical efficiency is the energy expended to do a given amountoof work output in performing a motor task. If a skilled performer can decrease the work done during a task, as evidenced in a lower task cost, then motor efficiency has increased. The
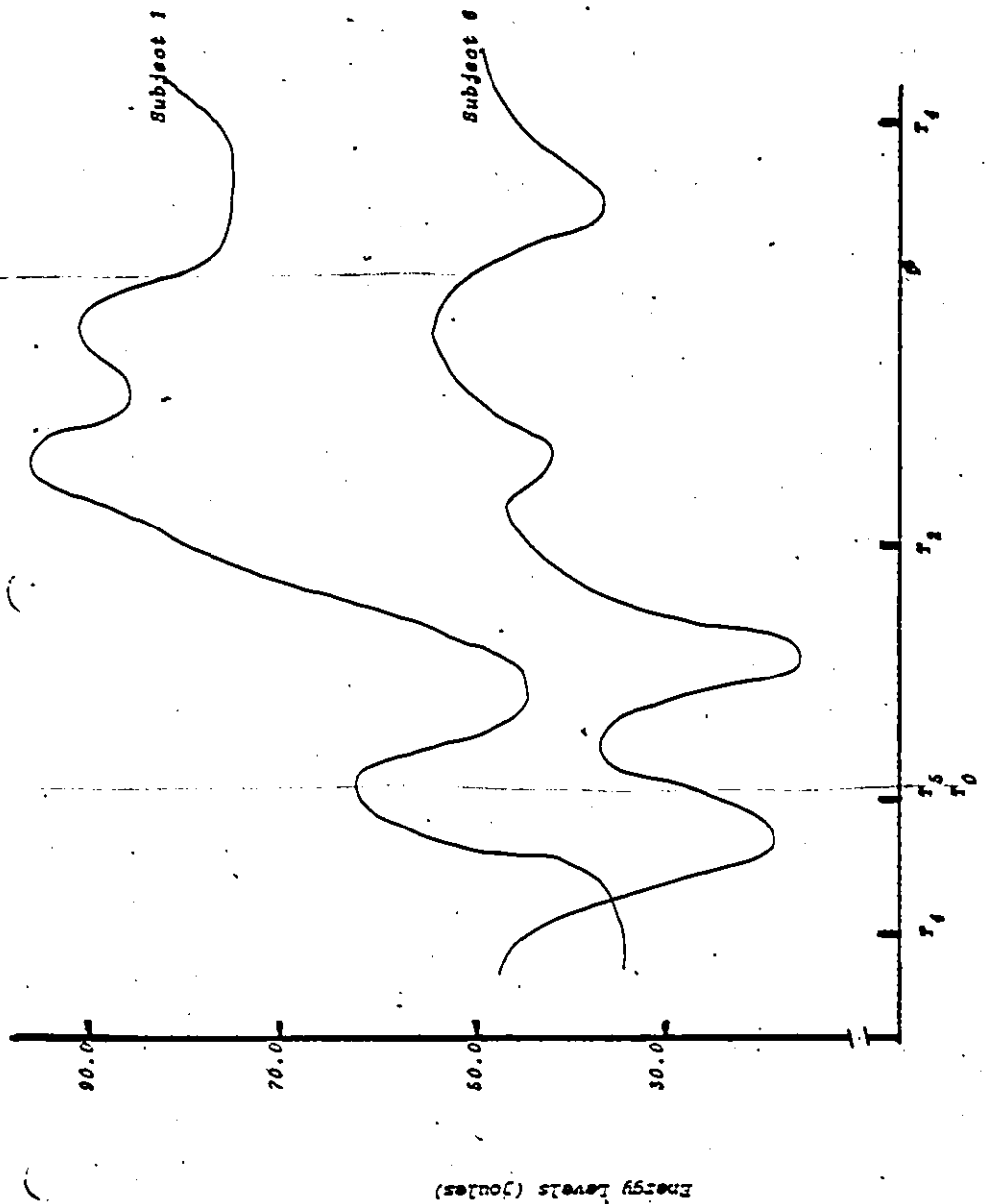
68

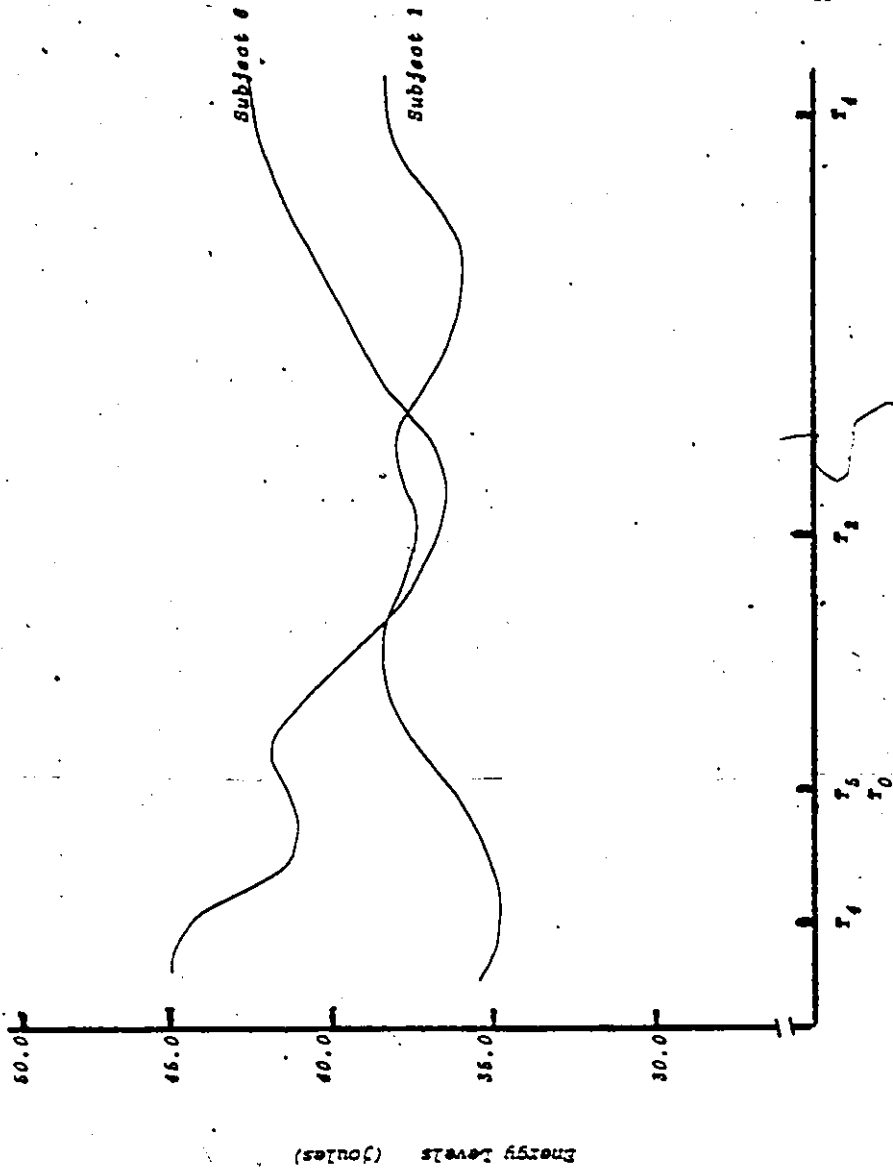Figure 8: Kinetic energy curves of the swing thigh for Subject 1 and Subject 6.

Figure 9: Potential energy curves of the swing thigh for Subject 1 and Subject 6.
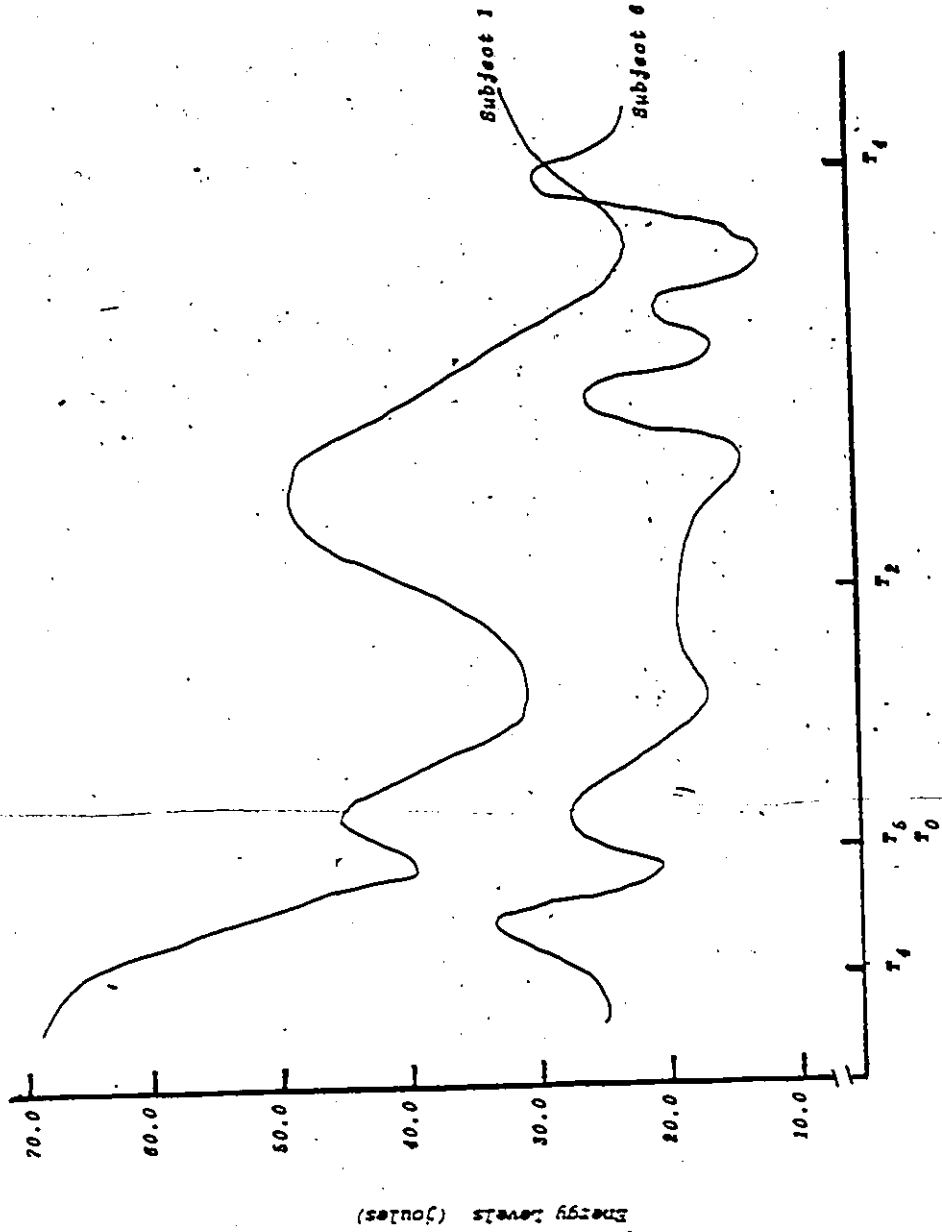
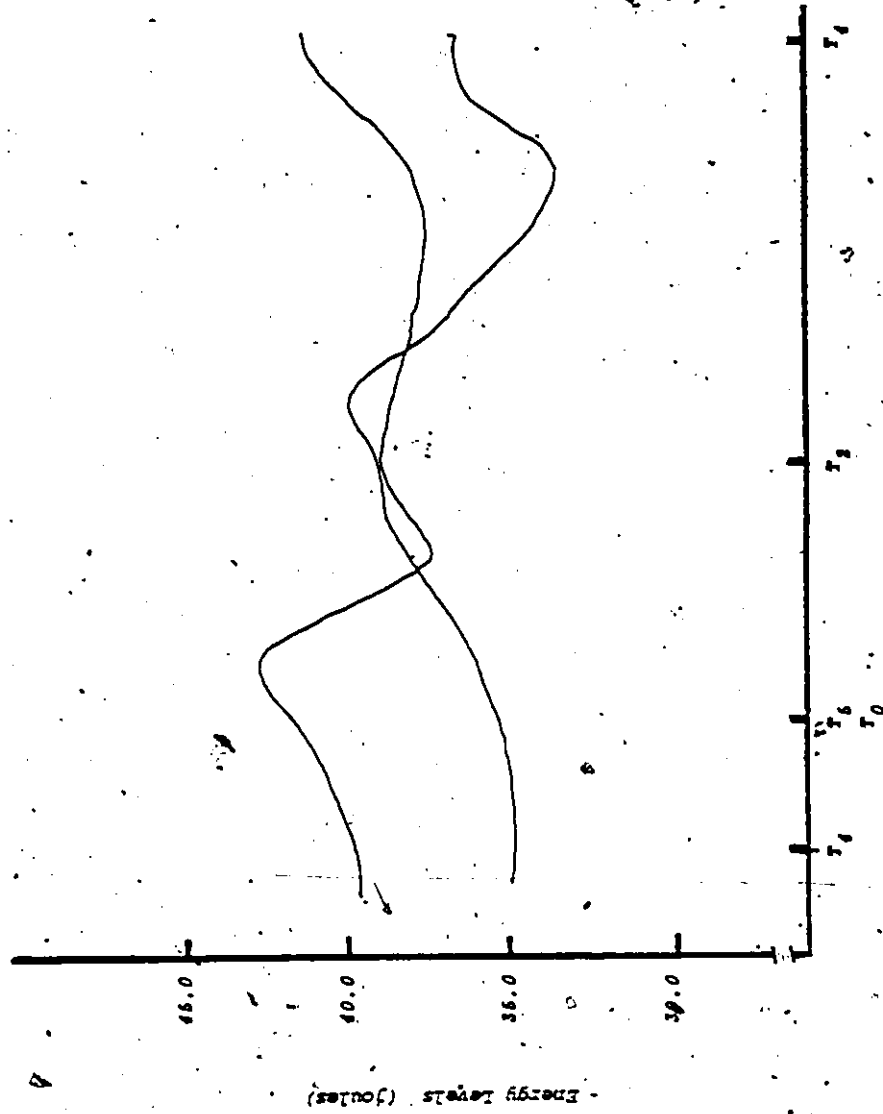Figure 10: Kinetic energy curves of the kick thigh for Subject 1 and Subject 6.

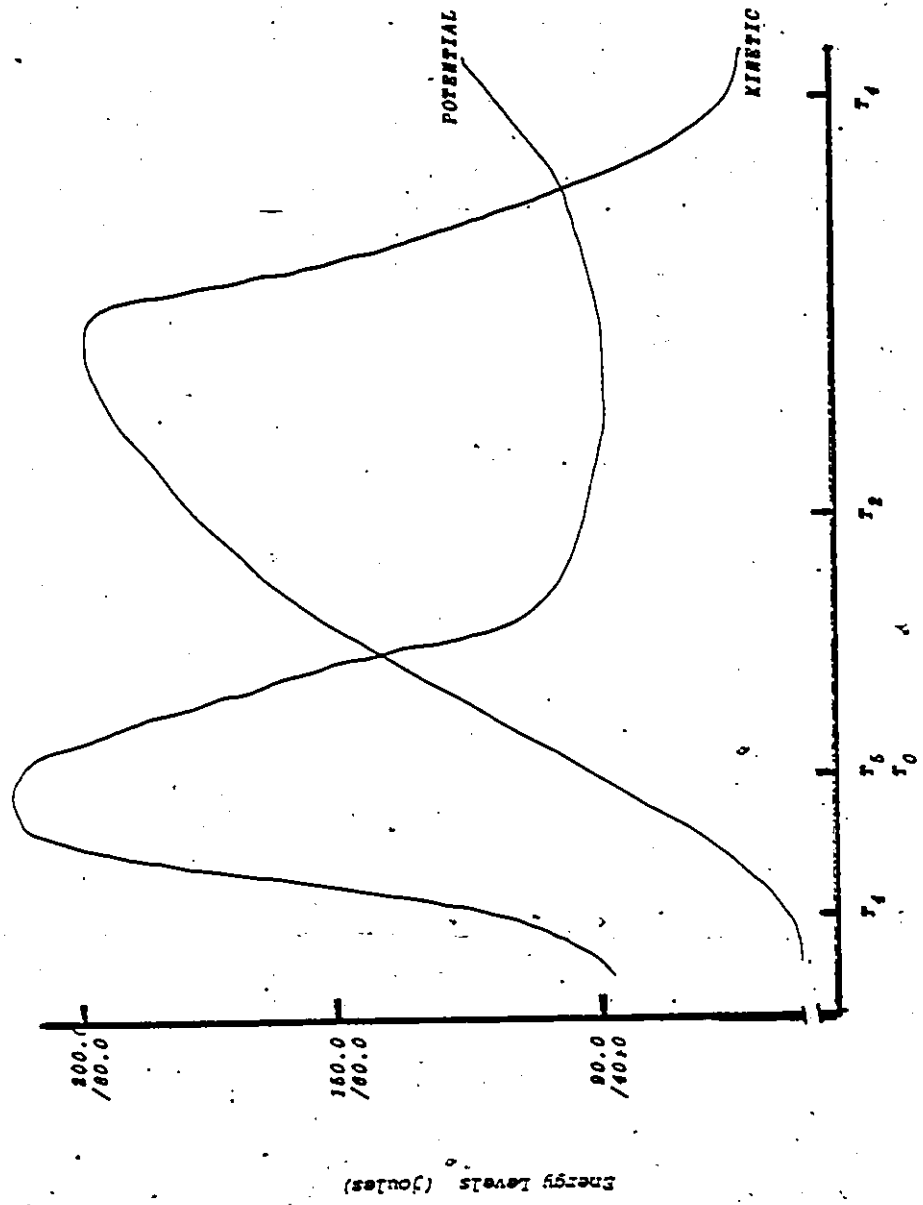Figure 11: Potential energy curves of the kick shank

Figure 12: Potential and kinetic energy curves of the swing shank for Subject 1.

higher work values of the elite skiers indicated a greater
generation of mechanical energy. However, the mechanical
work done per kilogram per meter, the task cost, did not
vary much between the two groups. Thus the motor efficiency
of the two groups would also be about equal. The higher
mechanical work output demonstrated by the elite competitors
appears to be the result of elevated energy transfers. The
use of energy transfers by the elite skiers may have affected
their mechanical efficiency, since it is based on the total
amount of energy utilized.

Examination of the energy curves can provide insight into
the efficiency of the performance. Cavagna et al (1977) re-
ported efficiency to be greater in running than in walking
through energy curve analysis. Walking involves a near-
perfect passive interchange of potential and kinetic energy.
The potential and kinetic energy curves are almost totally in
phase, one increases as the other decreases, and vice versa.
In running however, these curves overlap, indicating the trans-
fer of energy between segments. Examination of the energy
curves of the swing shank suggest this phenomena to be true
in cross-country skiing. The curves of the elite skier display
a greater overlap than do those of the skilled skier (Fig. 12).
Assuming a pendulum-like motion, the earlier increase in
kinetic energy of the elite skier's shank would suggest a
transfer of energy between the segments. Examination of the
energy curves of the swing thigh (Fig. 14) indicates a decrease

in both kinetic and potential energy levels at the .01 sec. point, for the elite skier. Energy appears to be flowing from the thigh segment into the shank, accounting for it's high kinetic energy level. The energy curves of the swing shank and thigh for the skilled skier (Fig, 13, 15) do not demonstrate as much overlap, and thus less between segment transfer.

The total energy transferred between the segments was substantially higher for the elite skiers than for the skilled, (48%). Individual between segment transfers, although not within the scope of this paper, can be calculated in the form of power flows across the joint centre. Power flow, or the rate of energy transfer, is the product of the power flow due to moments from muscle tension added to the power flow due to intersegment force (Quanbury et al, 1975). This rate of change of mechanical energy calculates the power required to decelerate and accelerate a segment at any instant in time.

To determine the two components of power flow, necessary moments and forces must be measured. In earlier studies, power flow to the system was calculated from joint forces and muscle moments obtained from force plate studies (Elftman, 1939). Methods employed in more recent research use kinematic information to calculate the rate of change of the total energy of the segment (Robertson and Winter, 1980). Most of the available data in the area of power flow deals with free walking and gait analysis. Zarraugh (1981), in computing the power requirements of the body as a whole, assumed perfect exchange
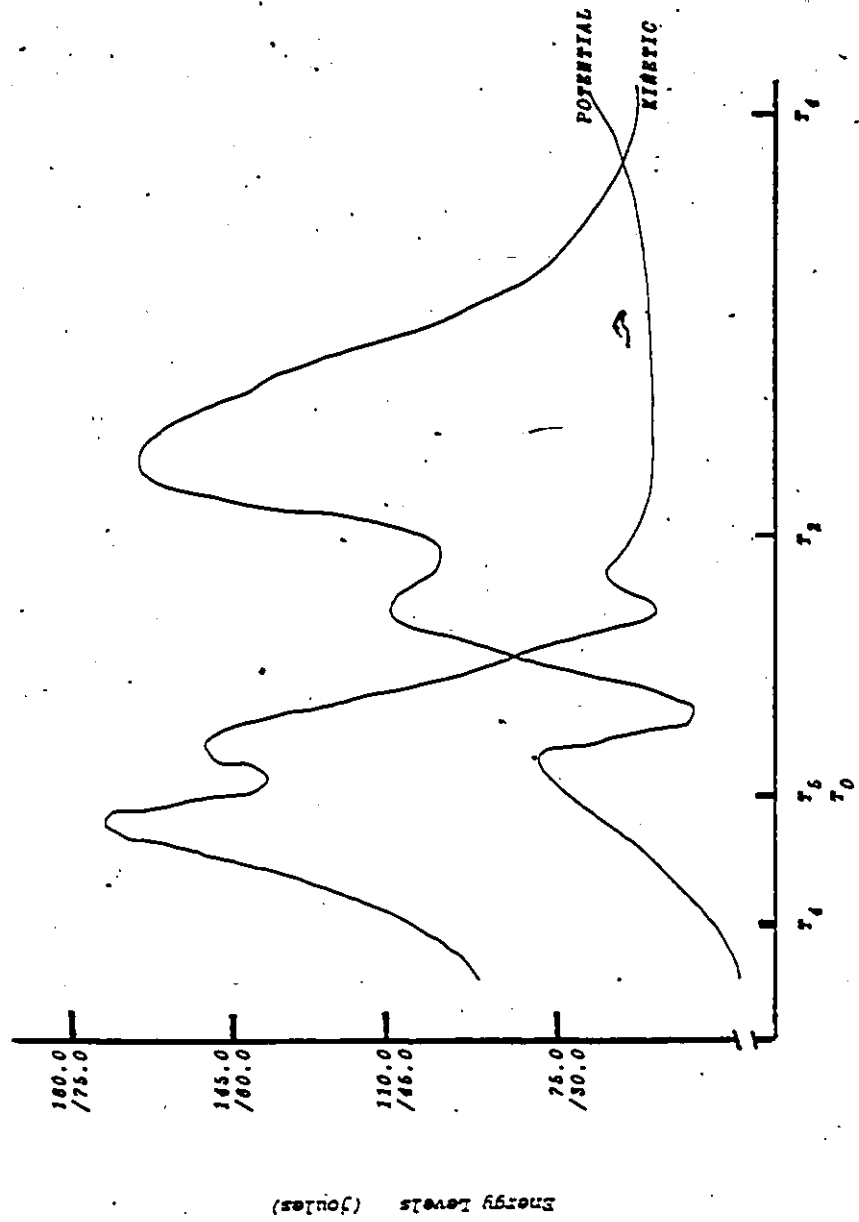
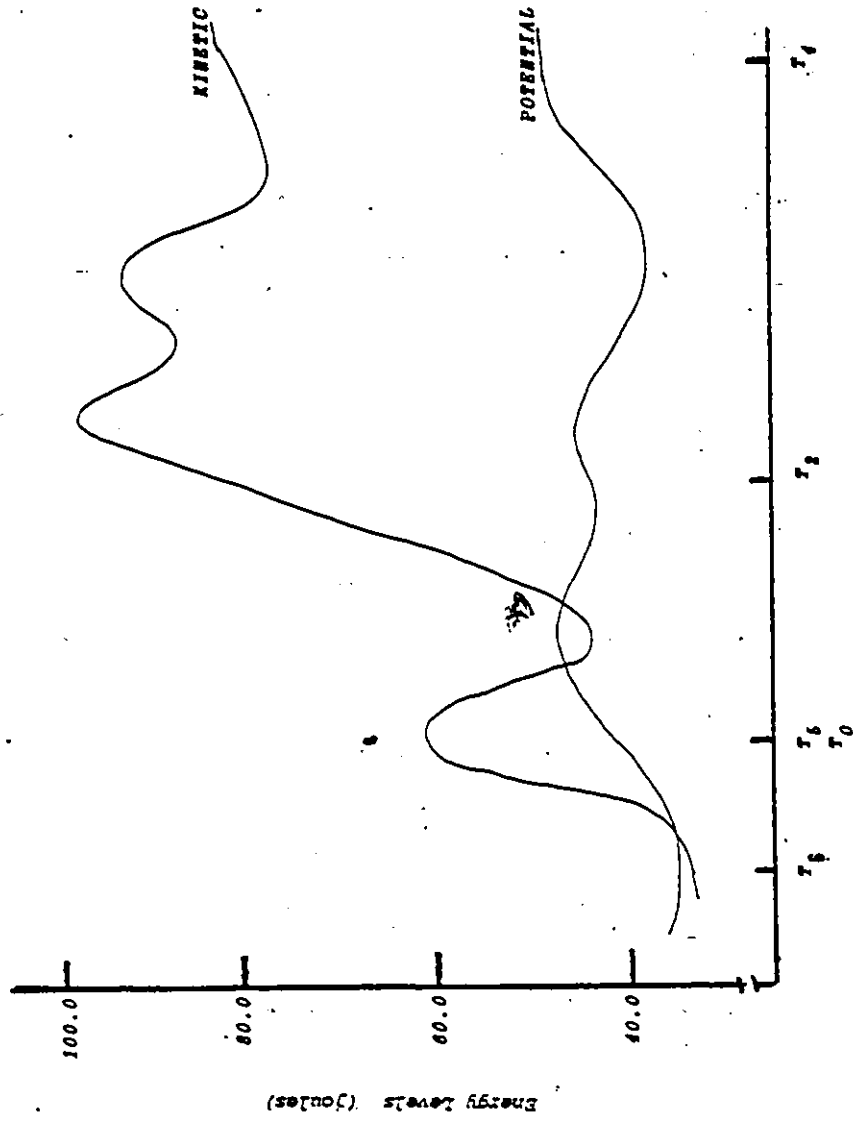Figure 13: Potential and kinetic energy curves of the swing shank for Subject 6.

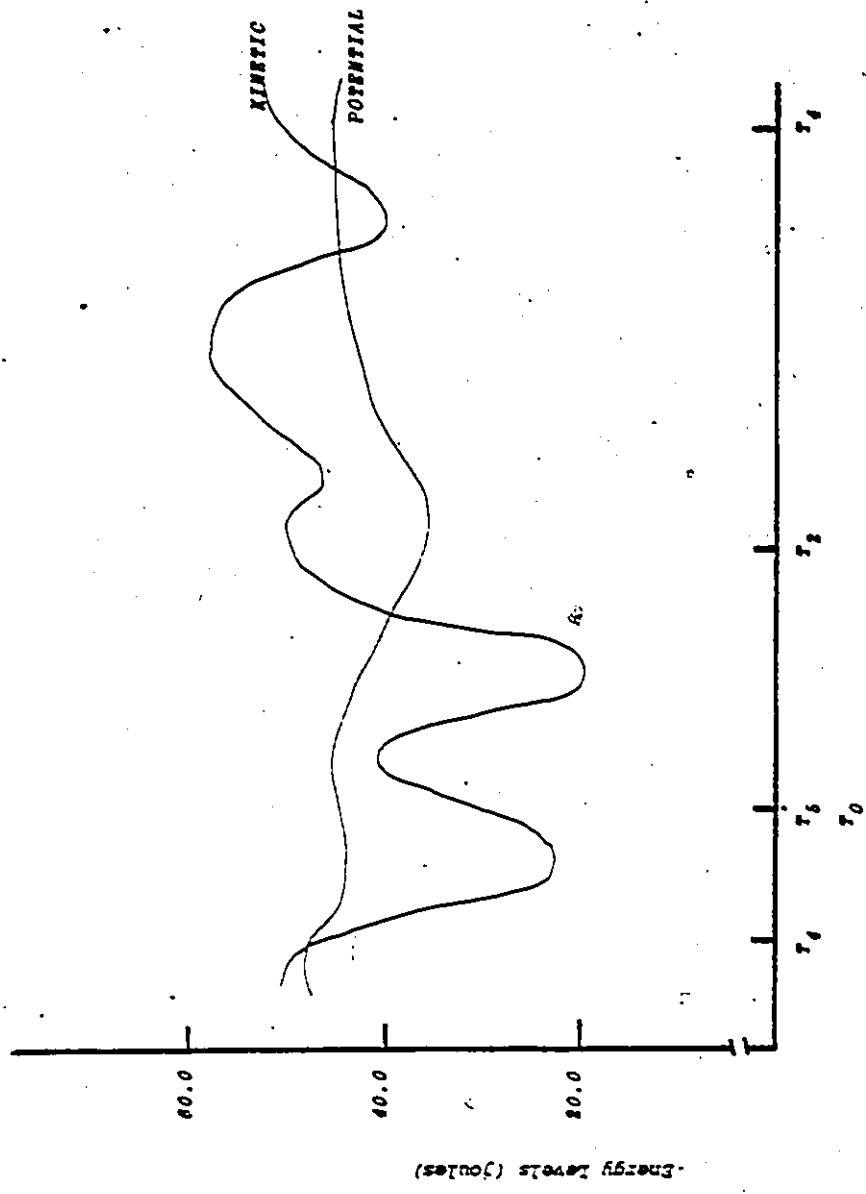Figure 14: Potential and kinetic energy curves of the swing thigh for Subject 1.

Figure 15: Potential and kinetic energy curves of the swing thigh for Subject 6.

of energy to occur between various body segments. Power flow
in the leg when it is accelerating is in the opposite direc-
tion although of equal value, to the opposite leg which is de-
celerating. The combination of these flows cancels each other
out and reduces the power requirements of the body. Such an
assumption would not hold in the study of the diagonal stride
since, although cyclic in nature, one segment does not decel-
erate at the same rate that the other accelerates. Therefore,
perfect exchange between the segments would not be possible.

In another gait analysis (Winter et al (1976b) the major
contributor to accelerating the thigh and shank forward and
upward during walking was found not to be hip flexion as pre-
viously thought, but power flow through the joint. As pre-
viously mentioned, power flows out of the thigh during the
recovery phase, aiding in the acceleration of the shank.
Energy may also be transferred to the body via the decel-
eration of the leg. It would be wise to assess the direction
of the energy flow during the recovery phase in later research
through power flow analysis.

According to research by Cavagna et al (1977), the cost
of mechanical energy changes is minimized by two energy-
conserving mechanisms. The first is the interchange between
potential and kinetic energy without the active intervention
of muscles. Secondly, energy can be conserved through the
recovery of mechanical energy stored during a preceding phase
of negative work. During such a phase, mechanical energy can

be stored in the elastic elements and then taken up from the surrounding tissue during the subsequent phase of positive work.

The interchange of potential and kinetic energy as a means of conserving mechanical energy was measured in the form of individual within segment transfers. The differences between sample groups, although not significant, have been examined in an attempt to understand how a greater skiing velocity was achieved by the elite competitors, and it's possible effect on the efficiency of the skiers.

Although the methods employed in this study did not include the computation of elastic recoil energy, analysis of the skill itself provides information on the restoration of elastic energy.

The part of the muscle which generates tension is called the contractile element. These elements are contained within connective tissue which aid in the production of tension. There are two types of connective tissue; the parallel connective component and the series elastic component. Hill (1950) emphasized the importance of the series elastic component in that it:

> "...acts as a buffer when a muscle passes
> abruptly from the resting to the active state,
> and it accumulates mechanical energy as the
> tension of the muscle arises...which can be
> used in producing final velocity greater than
> that at which the contractile component itself
> can shorten."

Cavagna et al (1968) hypothesized that previous stretching helps the contractile component to develop tension during

shortening. Later research revealed previous stretching to 'potentiate' the contractile component, allowing muscles to shorten actively against a force slightly greater than they are able to develop isometrically at their optimal length (Cavagna et al, 1977).

This stretching occurs when a muscle is in a state of eccentric contraction and negative work is being done. Subsequent shortening of the muscle occurs during concentric contraction when positive work is being performed. It is during movements where eccentric contractions are immediately followed by concentric contractions that energy restoration occurs. Bosco and Komi (1980) in studying drop jumps and countermovement jumps (jumps which include a preparatory movement), showed potential elastic energy to be implanted into leg extensor muscles during negative work. The stored energy was later used in subsequent positive work.

The utilization of elastic energy depends on the velocity of the stretch, the length of the stretch, and time between the stretching and subsequent shortening (Cavagna et al, 1977; Komi and Bosco, 1979). Komi and Bosco (1977) have also suggested the skeletal muscle fiber composition may influence the ability of the muscle to store and utilize elastic energy.

Through examination of the skill, it is possible to hypothesize where energy is being conserved through elastic recoil. The greatest total amount of elastic energy restoration appears to occur just prior to the kick thrust.

Following the recovery phase, both arms and legs are in a
state of eccentric contraction. This phase is immediately
followed by the kick thrust, in which all limbs are in a
state of concentric contraction. India (1979) found the
thrust phase to be responsible for increasing the velocity
of the skier to a maximum during the glide phase, a finding
supported by the results of this study. Perhaps the elite
skiers were able to absorb more energy, by way of higher
energy levels, during the recovery phase and used it later
to increase the mechanical work output during the thrust
phase. Solimon (1977) found the kick thrust to occur
earlier in the elite skiers, a finding supported by this
study. Since the time between the stretching and shortening
of a muscle affects the potentiation of the contractile
element, a quicker leg kick would result in greater res-
toration of the elastic energy stored.

Another portion of the stride which may be aided by
elastic energy is the recovery phase. Energy is being ab-
sorbed by the quadriceps muscle group, that is, it is in
a state of eccentric contraction, during the kick phase of
the stride. This phase is followed by the recovery phase,
in which the quadriceps are in a state of concentric con-
traction. Therefore, energy is flowing from the muscles to
the limbs. The higher leg kicks displayed by the elite
skiers generates higher potential energy levels resulting

in greater absorption of energy by the muscle and a subsequent greater restoration of the elastic energy stored.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The purpose of this study was to determine the internal mechanical work output and energy transfers of elite and skilled female cross-country skiers. Six racers filmed at the 1979 North American Cross-Country Ski Championships were analyzed. Three of the subjects were international level skiers, and three were provincial level skiers. A high speed Locam camera was used at a speed of 100 frames per second.

Summary

Kinematic and kinetic data was compiled through film analysis and the aid of a Fortran computer program. In addition to the kinematic variables, three work values, (Ww, Wn, Wwb) were calculated. Subsequent analysis revealed significant differences in the total amount of energy transferred. The individual body segments transfers provided limited insight into the manner in which energy was transferred. In an attempt to speculate how skier velocity was affected by energy transfer and absorption, the results were discussed in terms of energy transfer, mechanical

efficiency, elastic energy restoration and power flow analysis. Possible methods of determining energy absorption and power flow were discussed in an attempt to clearly understand the pattern of energy transfer and its importance to the mechanical cost of movement.

Conclusion

The number of subjects greatly affected the statistical analysis of the data, resulting in few significant differences between the two groups. Although not significantly different all the work values (Wn Ww, Wwb) were higher for the elite skiers than for the less skilled skiers. Both groups showed similiar task costs. A significantly higher total amount of energy was transferred for the elite skiers. The separate components, between and within energy transfers, although much higher for the elite skiers, did not differ significantly. An analysis of individual body segment transfers revealed no significant differences to exist between the groups in the amount of energy transferred within individual segments. However, a few segments did show a marked difference, especially the kicking shank and thigh, and the pushing upperarm.

The mechanical energy analysis, particularly the energy curves, revealed some differences between the groups. The elite skiers exhibited higher levels of potential and

kinetic energy, except for the swing thigh, which displayed
higher potential energy values. The higher values may be
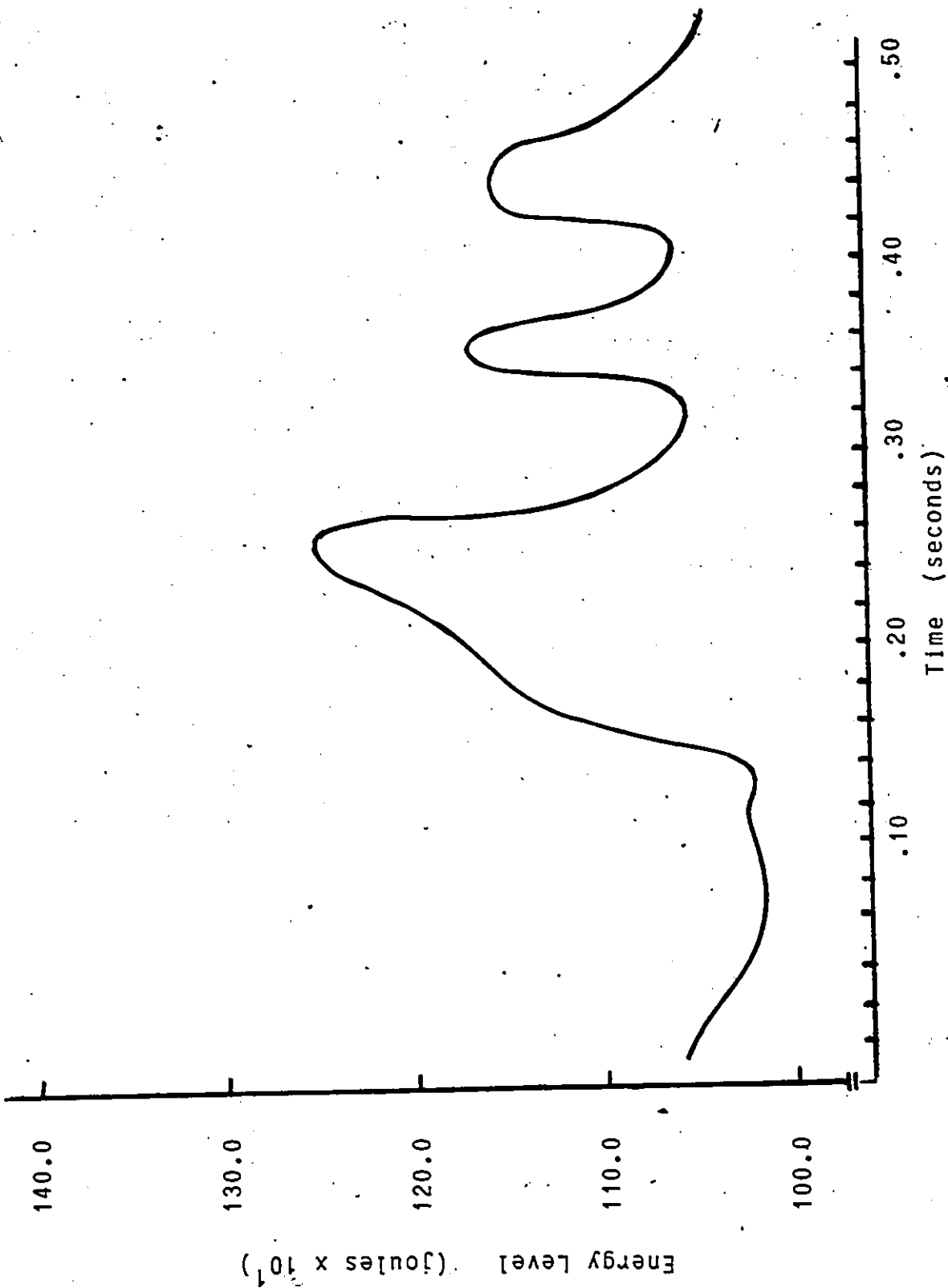due to the more upright body position of the skilled skiers.

The restoration of elastic energy appears to play an
important role in the conservation of energy. More research
is needed in this area to accurately determine the cost of
the utilization of stored energy and it's effect on the
metabolic expenditure and efficiency of a performer. Fur-
ther analysis of elastic energy in human performance would
include muscle biopsies to determine muscle fiber composi-
tion and its effect on elastic energy recoil.

The calculation of the mechanical work output parti-
tioned for each phase of the diagonal stride would provide
valuable information into velocity differences between the
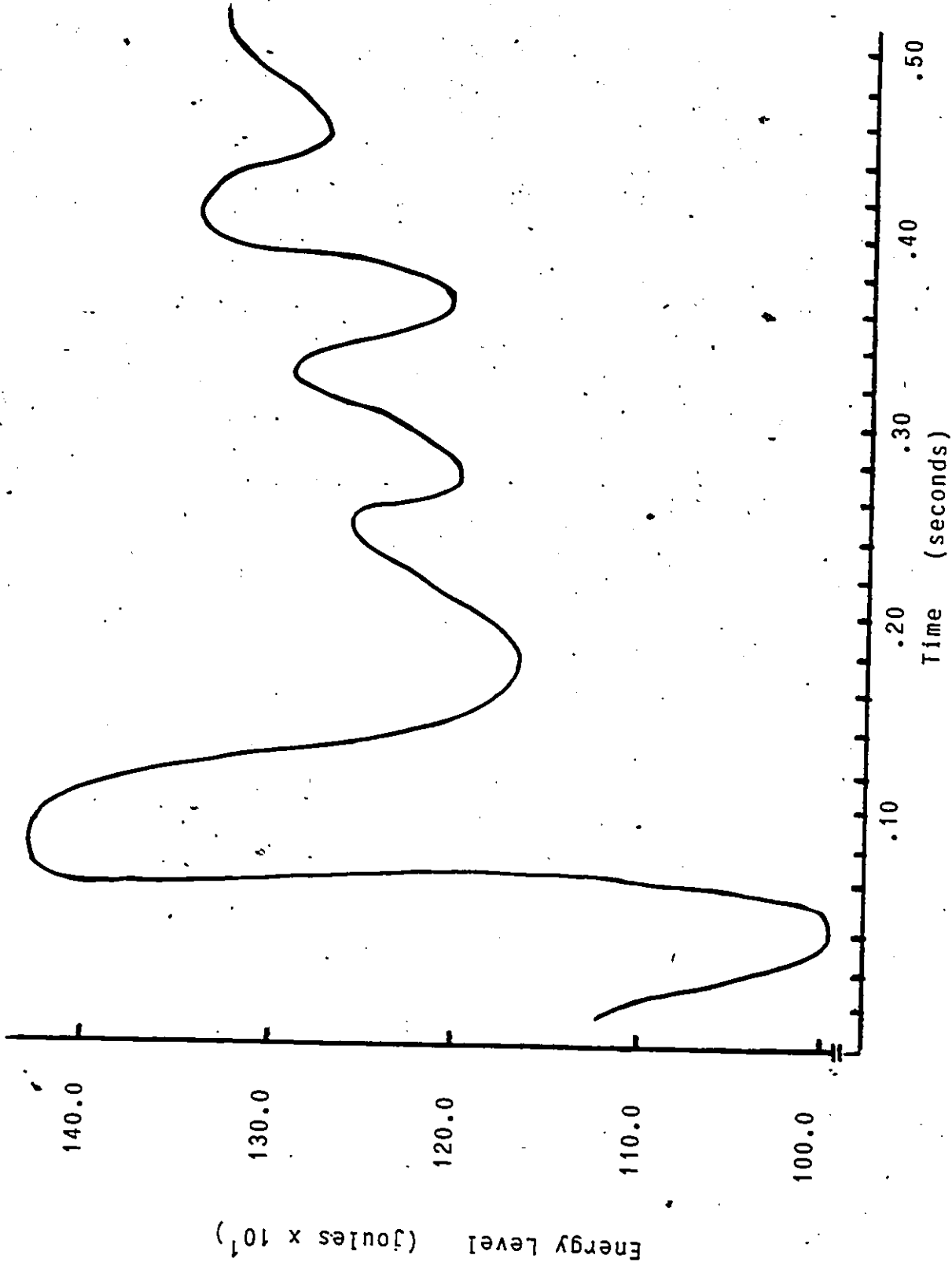elite and skilled sample groups.
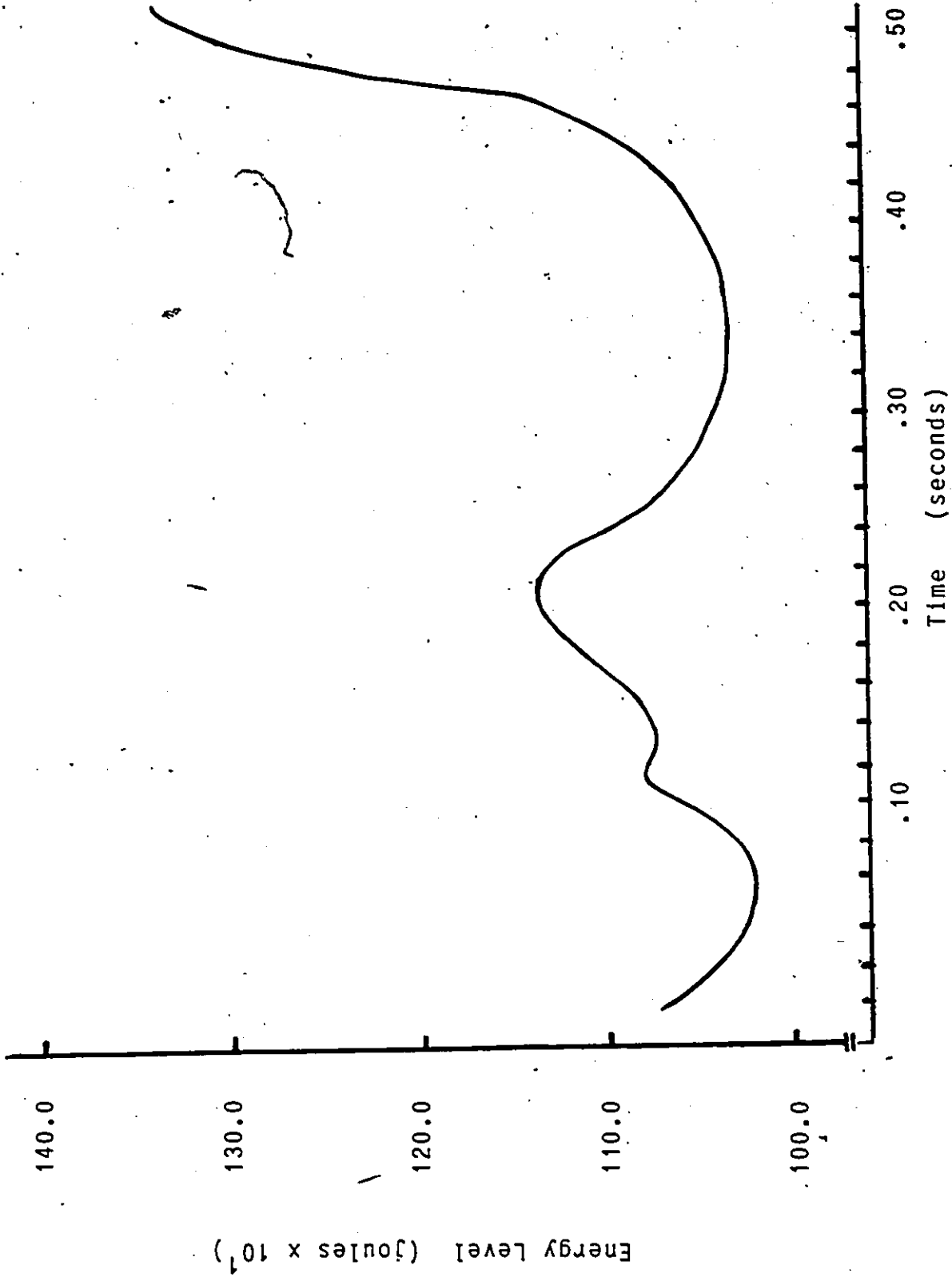
APPENDIX A

Auxillary Graphs
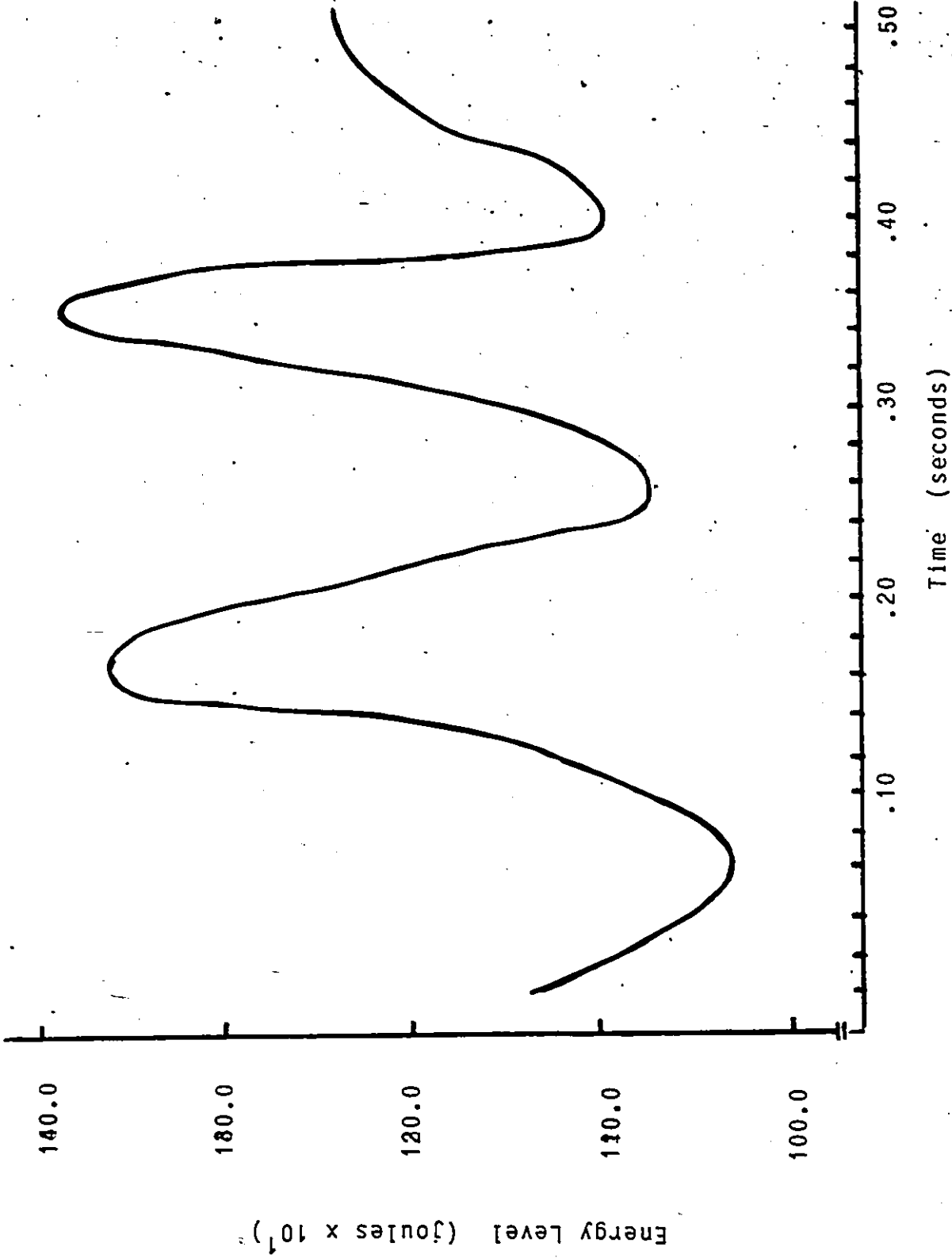
Total body energy curve for Subject 2

Total body energy curve for Subject 1

Energy Level (joules x 10^1)

Time (seconds)

Total body energy curve for Subject 6
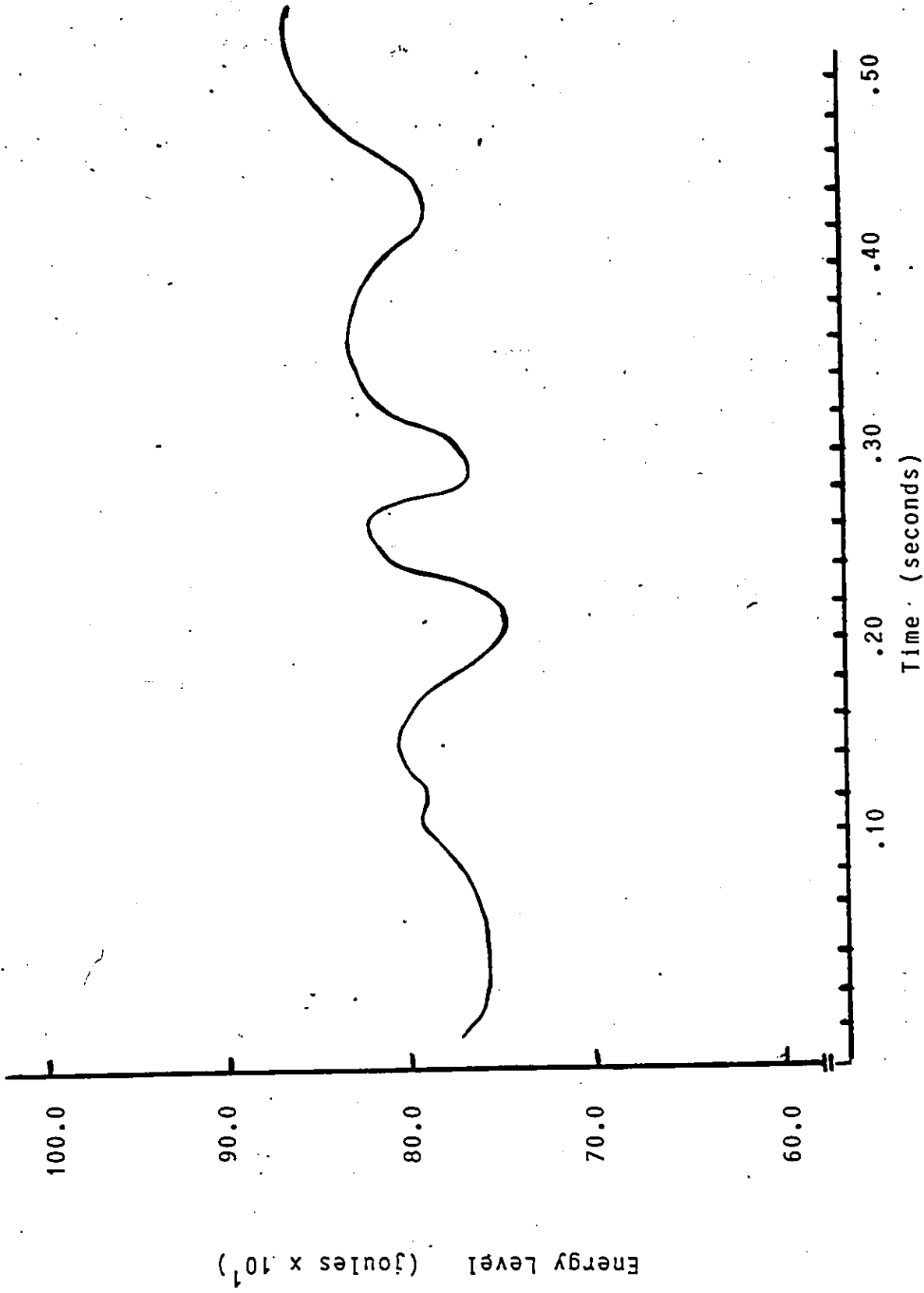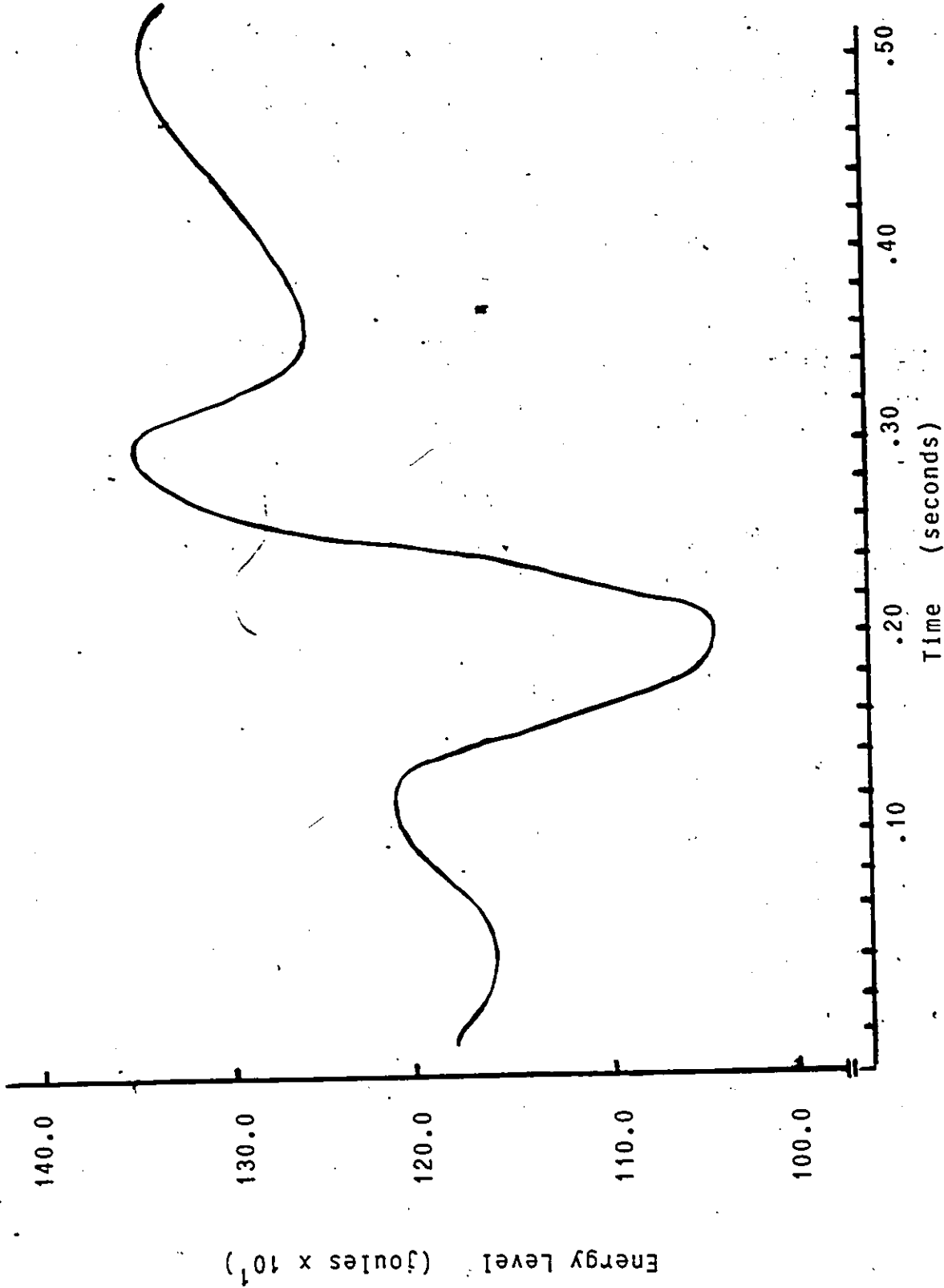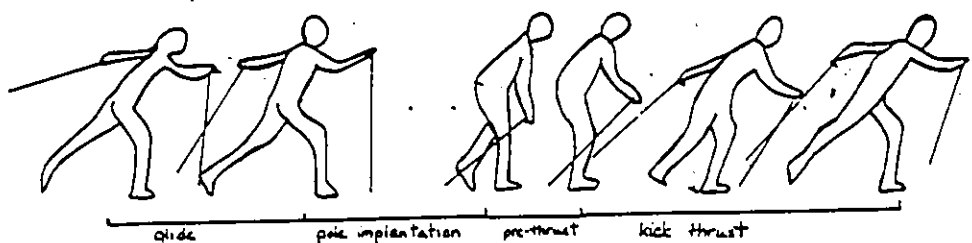
Total body energy curve for Subject 4

Total body energy curve for Subject 5

Time (seconds)

Energy Level (joules x 10^1)

Total body energy curve for Subject 3

Potential Energy (J) — 200, 145, 90.

Kinetic Energy (J) — 80.0, 40.0, 20.0

T4   T5   T1   T2   T3   T4

glide   pole implantation   pre-thrust   kick thrust
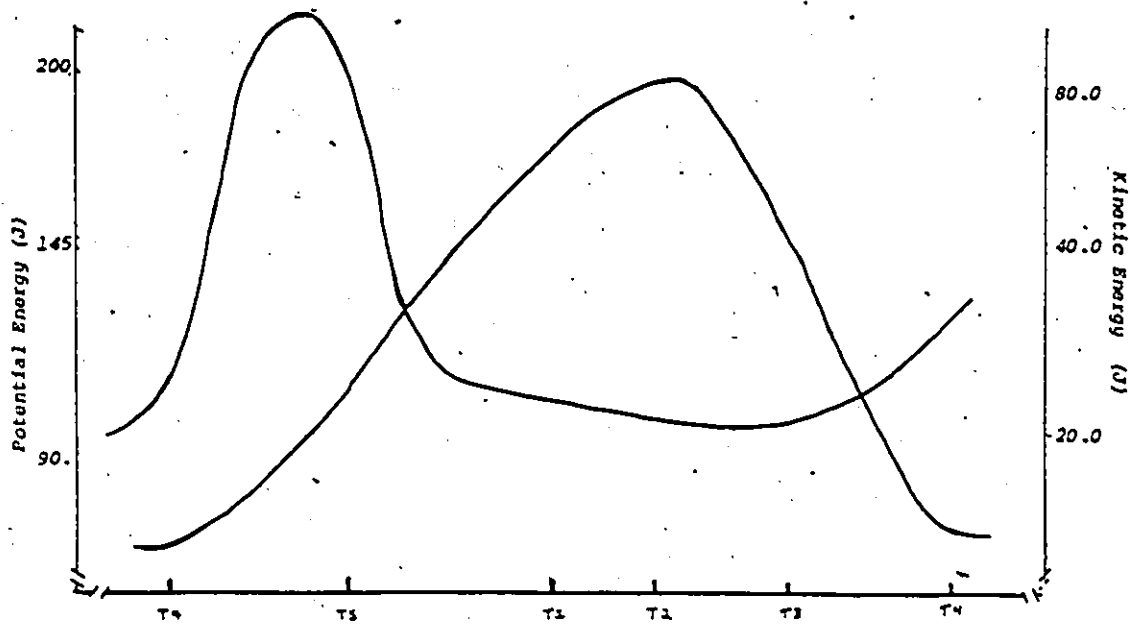
-low PE value result
of lower leg kick
-indicates use of
muscular force in
deceleration of kick
shank
-covered less distance

-peaks identify use
of muscular energy
rather than gravitational
force

-KE peaks occur prior to
onset of kick; indicative
of lower velocity values
-may result in higher
metabolic cost in attempt
to maintain speed

glide	pole implantation	pre-thrust	kick thrust
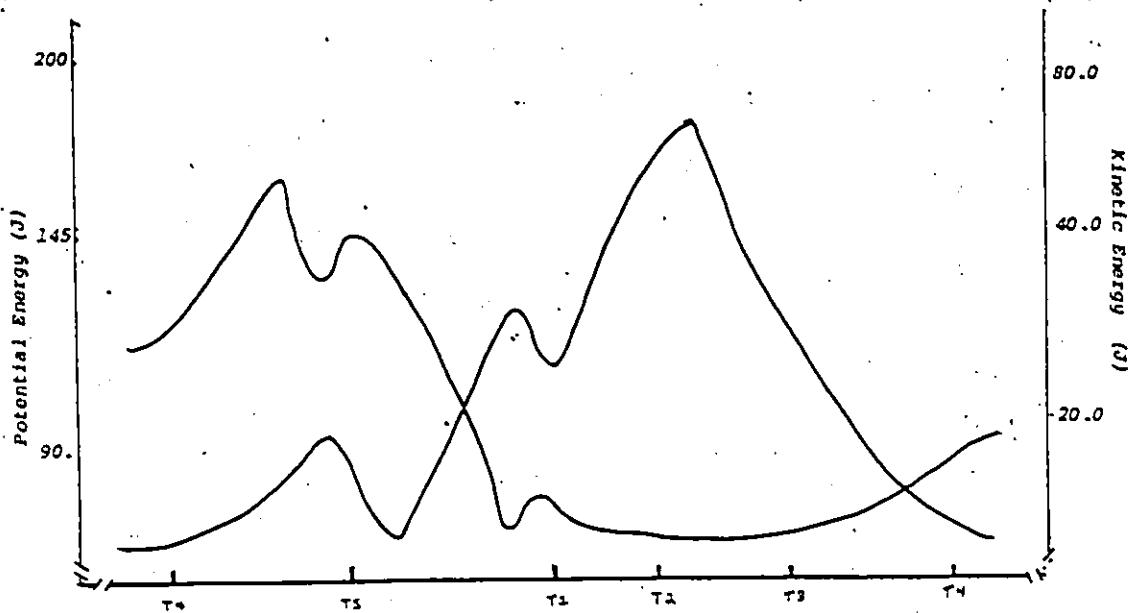
-large PE value as
a result of higher·
leg kick
-increased PE
generates higher KE
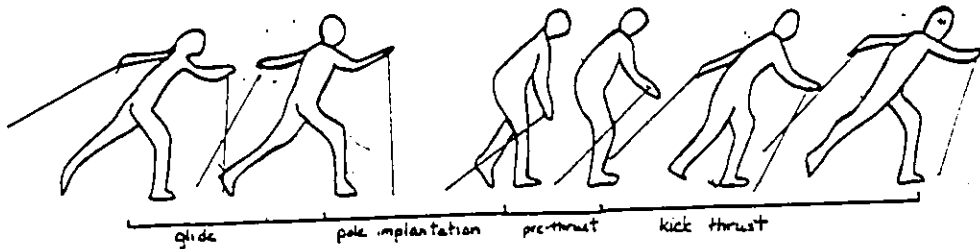value in recovery
-covered greater
distance in same
time

-high PE and KE
values account for
high within segment
transfers
-slope indicates
smooth interchange
of energy and the
use of gravitational
forces

-high KE energy throughout
kick phase of support ski
indicative of high KE at end
of recovery
-covered less %. total distance
in same time

APPENDIX B

Statistical Analysis

T-Tests

STATISTICAL ANALYSIS OF KINEMATIC VARIABLES

	Step Length	Step Time	Step Rate	Horizontal Velocity	Mechanical Task Cost
Elite Mean	2.17	.51	1.95	4.24	4.22
Skilled Mean	1.75	.52	1.91	3.35	4.55
SD Elite	.110	.015	.077	.056	.434
SD Skilled	9.99E-03	5.77E-03	.023	.045	1.580
t-ratio	6.60*	-1.41	.926	21.07*	-.348

$t_{.05} = 2.776; p .05$

$df = 4$

STATISTICAL ANALYSIS OF MECHANICAL WORK

	Mechanical Work (Wn)	Mechanical Work (Ww)	Mechanical Work (Wwb)
Elite Mean	1037.12	678.54	511.76
Skilled Mean	672.12	547.03	442.76
SD Elite	177.23	73.74	42.34
SD Skilled	292.44	236.78	182.73
t-ratio	1.84	.918	.637

$t_{.05} = 2.77;$ p .05

df = 4

STATISTICAL ANALYSIS OF ENERGY TRANSFERS

	Energy Transfer Within Segments	Energy Transfer Between Segments	Energy Transfer Total
Elite Mean	33.18	18.86	52.04
Skilled Mean	18.66	12.71	31.37
SD Elite	13.43	11.14	2.38
SD Skilled	2.86	2.68	3.69
t-ratio	1.83	.930	8.14*

t.05 = 2.776; p..05

df = 4

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