

MECHANICAL AND METABOLIC CORRELATES IN
THE MUSCULAR WORK OF STEPPING WITH
SPECIAL REFERENCE TO TENSION-TIME INTEGRALS.

by

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ABSTRACT

Other investigators have reported correlation between the mechanical parameter of "tension-time" (defined as the definite time integral of the externally-applied force over a chosen time interval) and the metabolic energy expenditure of isometric muscular action. This study investigated whether the tension-time integral remained a useful correlate of physiological effort in a gross, dynamic muscular work task. Bench-stepping was the work task chosen, and the investigated quantities were varied by altering stepping rate (36, 30, 24 and 18 cycles per min).

Metabolic energy consumptions were calculated from respiratory gas measurements. From cinematographic records, distance-time curves of movements of the centre of gravity throughout complete step cycles were obtained. By numerical differentiation, velocity-time and acceleration-time curves were calculated, and, by adjustments to the latter, tension-time curves were thus obtained. Integration between selected time-limits yielded tension-time integrals.

Tension-time integrals were considered in three ways. (i) fixed-time integrals, in which the time interval considered was constant for different work tasks (ii) action-phase integrals, in which the time intervals considered were those of defined movement phases. (The duration of these intervals varied as stepping rate varied.) (iii) work-phase

integrals, in which the time intervals considered were those of particular types of muscular action (concentric, eccentric and static).

It was shown that any tension-time integral is a linear multiple of the duration of the phase considered, and equal to $m.g.t$ where m is the mass of the body, g the acceleration due to gravity, and t the phase duration. Fixed-time tension-time integrals were therefore constant for different work tasks and bore no relation to their physiological costs.

Action-phase integrals for selected movement phases of different work tasks were multiples of the duration of the phases chosen : since the durations of the several movement phases in a complete step cycle were shown to vary in a complex manner as stepping rate altered, and since the metabolic energy cost-stepping rate relationship was shown to be linear, action-phase tension-time integrals varied in a complicated way in response to changes in stepping rate.

Work-phase integrals, being special cases of action-phase integrals, were also shown to be not useful as correlates of physiological effort.

The ratio of the mechanical work done in any phase, expressed as the tension-distance integral, $\int T.ds$, to the tension-time integral, $\int T.dt$, was demonstrated to equal the average velocity of movement during the phase considered.

It was concluded from this study that tension-time integrals, as defined, are not useful correlates of metabolic energy cost in dynamic

muscular work tasks. Doubt is cast on the general validity of using such integrals, however they be considered, to interpret or predict metabolic energy costs of dynamic muscular work.

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CHAPTER I

INTRODUCTION

This study investigates a method of measurement and correlation of mechanical and metabolic parameters of muscular performance.

Function of Muscle

Human muscle has three functions:

- i) to provide heat and so help maintain temperature homeostasis
- ii) to initiate and maintain movement
- iii) to oppose movement

The first of these is illustrated in the resting metabolic state of muscle when no excitatory electrical activity is discernible: heat is also produced as a by-product when muscle fulfils its other functions.

The second function is shown in the performance of mechanical work on the external environment, as in raising a load against the force of gravity. The third is apparent in maintaining a load stationary, or in lowering it vertically under control; in both latter cases the tendency of an external force to cause a different motion is modified.

Muscle as a thermodynamic system

In fulfilling its functions muscle may be considered as a thermodynamic system, receiving energy of one sort, chemical potential energy supplied by nutrients, and transforming it into energy of another sort. The transformed energy is apparent either as heat, or as the performance of mechanical work on the external surroundings. The internal energy

change (ΔE), the heat evolved (q) and the mechanical work done (W) are related in accordance with the First Law of Thermodynamics:

$$\Delta E = q - W \quad \dots (1)$$

In the sign convention used in Equation 1, the heat added to the system and work done by the system are both counted positive.

Biological systems are special in a thermodynamic sense since changes occurring within such systems do so under conditions which are both isothermal and isobaric. Such systems are more conveniently described in terms of enthalpy changes rather than internal energy changes since the enthalpy concept automatically takes into account changes in volume. Enthalpy changes (ΔH) are related to internal energy changes and volume changes (ΔV) by the equation:

$$\Delta H = \Delta E + p \cdot \Delta V \quad \dots (2)$$

where p denotes the constant pressure.

Furthermore, in biological systems, volume changes are generally insignificant because chemical changes occur in solution. In these special systems, 'internal energy changes' and 'enthalpy changes' are synonymous terms. This is the case for changes occurring in muscles.

Electrical stimulation of a muscle causes an internal enthalpy change as a result of a triggered, spontaneous chemical transformation. One part of the enthalpy change, the free energy portion (ΔG), is

transferable from the system in mechanically-useful form. This portion is often termed the Gibbs free energy. In isovolumic changes, such as occur in muscles, it corresponds to the maximum work content or the Helmholtz free energy (used by physicists and engineers). The remaining portion of the enthalpy change, the entropy change (ΔS), is not transferable from the system in useful form. It is a measure of the change in randomness of structural arrangement of the components composing the system.

The relationship between these several quantities is governed by the Second Law of Thermodynamics and is stated thus:

$$\Delta H = \Delta G + T \cdot \Delta S \quad \dots (3)$$

T is the constant absolute temperature.

Theoretically, all of the free energy may, through some coupling mechanism, be converted to externally-performed mechanical work. In practice, only a portion of it is so converted, the other portion, denoted q_{irr} , being irreversibly degraded to heat energy. This energy transformation is subject to the strictures of the First Law, and is expressed as:

$$\Delta G = -W - q_{irr} \quad \dots (4)$$

Thus, an available energy (ΔG) yields a useful energy output, W . The degraded heat, q_{irr} , is regarded in this instance as waste.

Concept of Efficiency

These considerations lead naturally to the concept of efficiency as a measure of the effectiveness with which available energy is actually used. The efficiency of an energy transformation process is therefore defined as:

$$\text{Efficiency} = \frac{\text{Useful energy output}}{\text{Free energy made available}} \quad \dots (5)$$

This ratio is usually expressed as a percentage. In the context of the transformation summarised in Equation 4 it follows that:

$$\text{Efficiency} = \left| \frac{W}{\Delta G} \right| \quad \dots (6)$$

$$\text{or Efficiency} = 1 - \left| \frac{q_{irr}}{\Delta G} \right| \quad \dots (7)$$

Whatever the true nature of energy transformation, its efficiency is an important parameter, for it measures the effectiveness of the system as an energy converter.

In order to assess the efficiency of working muscle(s), defined in accordance with Equation 5, it is necessary to determine two of the quantities; free energy made available; useful energy output; wasted energy.

Which of these is determined, and how, is a matter of some arbitrariness. For example, the choice of methodology used in determining the free energy will be contingent upon whether isolated muscles or

muscles in vivo are used; whether macroscopic or microscopic measurement techniques are being employed; or whether one, several, or all of the complex of component changes are being assessed for their efficiency. This discussion will be returned to later.

Work and Efficiency: Concentric and Eccentric Muscular Action

In concentric muscular action, that is muscle shortening on stimulus to contract, the useful energy output of the muscle is equal to the amount of external mechanical work performed. For isotonic (i.e. constant tension) contraction the work done is equal to the product of the tension (T) exerted and the distance (s) through which its point of application moves in the direction of the force (i.e. T.s.). If the force is variable in magnitude, the work done is equal to the definite integral of the product T.ds, the limits of the integration being the appropriate distance limits of the dynamic action (i.e. $\int_{s_1}^{s_2} T.ds$). In both cases the muscle is said to perform positive work, the units of which are dyne cm.

The efficiency of the muscular work performance then becomes, from modification of Equation 5:

$$\text{Efficiency} = \frac{\text{External mechanical work done}}{\text{Free energy made available}} \dots \dots (8)$$

If a muscle is forced to lengthen under stimulus to contract it is said to undergo eccentric contraction and to perform negative work. The same considerations apply to the quantification of the work done as in the case of concentric contraction. It is noted though, that

In this case work is done on the muscle by the external agent rather than by the muscle. However, the muscle has still applied force through a certain distance and the efficiency of performance is again expressed by Equation 8.

It is clear that when muscles undergo concentric or eccentric action, the various energy relationships are perfectly consonant with the conceptual framework of classical thermodynamics and classical mechanics. In both cases the efficiency of the energy interchange is the ratio of the external mechanical work to the free energy supplied.

Work and Efficiency: Isometric Muscular Action

However, concentric and eccentric action constitute only one facet of muscular performance-namely dynamic action. It is often necessary for muscles under stimulation to apply tension to an external body without moving it-for example when attached to a very large mass. The muscle in static or isometric action performs no external work; although force is being applied externally, no movement is occurring, and therefore the product which defines mechanical work is zero.

The maintenance of tension requires a free energy release in the muscle: but because the mechanical work done is zero in such cases, it is misleading and confusing to refer to "static work" or "isometric work" as many authors have done (e.g. Monod, 1956; Starr, 1951). The suggestion first made by Cathcart, Bedale and McCallum (1923), that

the energetic interchanges occurring during isometric action be referred to as static effort, or isometric effort, will be adopted here.

The question arises of how the efficiency of isometric effort is to be evaluated. Utilizing the concept derivative from classical work notions (Equation 8), it follows that the efficiency of all isometric work must be zero: again, it does not seem possible to differentiate between different gradations of isometric force application in their relationship to thermodynamic interchanges occurring. Thirdly, there seems to be no provision for accounting the mechanical expressions of dynamic and static muscular action in similar terms which fit a consistent scheme of thermodynamic analysis.

These difficulties will be considered in relation to suggestions put forward by Starr (1951): Banister (1963): Banister, Ribisl, Cureton and Abbott (1964): and Banister (1970). In order to define clearly the problems investigated in the present study, these suggestions are examined.

Tension-time integrals

Starr (1951) suggested that physiological effort in both dynamic and isometric muscular action could be expressed in similar mechanical units. He proposed the criterion mechanical quantity to be the product of the externally-applied force and its time of application: this was referred to as the tension-time parameter of the muscular performance. The units of measurement are dyne sec.

This system of measurement was illustrated for the dynamic

work-task of weight-lifting and Starr claimed validity and usefulness of his method on the basis of results yielded in performing the work-task at two different lifting rates (See Review of Literature).

* Tension-time integrals and Acceleration-time curves

In order to assess the tension-time parameter Starr recorded the weight-lifting action cinematographically. A distance-time curve (s vs. t) describing the movement of the weight was plotted. The first time-derivative of this yielded the velocity-time curve (v vs. t), and the second time-derivative the acceleration-time curve (a vs. t). The abscissal axis of this graph was displaced - |g| units, yielding an adjusted acceleration-time graph. The area between this displaced axis, the curve, and the limit values of the independent variable, when multiplied by the mass of the subject, gives the tension-time integral. This is proved as follows:

If a body is raised vertically such that it has, at any instant, an observed acceleration $a \text{ cm sec}^{-2}$, then the net force acting on the body is $T + m.g.$ (T is the applied force measured in dyne; g is the acceleration due to gravitational attraction at the earth's surface; and m is the mass of the body being raised.) All quantities T, g and a are vector and positive in the vertically-upward direction. Then

$$T + m.g. = m.a$$

$$T = m.a - m.g$$

$$T = m (a-g)$$

$$T \cdot dt = m (a-g) \cdot dt$$

$$\int T \cdot dt = \int m (a-g) \cdot dt \quad \dots (9)$$

$$\int_{t_1}^{t_2} T \cdot dt = m \int_{t_1}^{t_2} (a-g) \cdot dt \quad \dots (10)$$

That is, the force-time integral between limits t_1 and t_2 is equal to the mass of the body raised times the area enclosed by the acceleration curve, the limits t_1 and t_2 of the independent variable, and the abscissal axis displaced g units. Since the vertically upward direction has been taken as positive, then $g = -981 \text{ cm sec}^{-2}$ and the axis is therefore displaced downward.

Similarly a force-distance integral may be derived from an adjusted acceleration-distance curve. Typical forms of both adjusted acceleration-time and adjusted acceleration-distance curves are shown in Figure 13 (page 42).

These tension-time and tension-distance integrals will be investigated in the present study. The tension-time integral will be examined as a measure of metabolic effort in a gross muscular work task.

Interconversion of Tension-Time and Tension-Distance Integrals

An extension was made to Starr's ideas by Banister (1963), Banister Ribisl, Cureton and Abbott (1964); and Banister (1970). It was suggested that a simple interconversion of tension-time units (i.e.

Starr's units of physiological effort, $\int T dt$) and the classical work units might be possible: "There may be a transform function between the two with dimensions of cm sec^{-1} ." (Banister, 1963). A similar notion was clearly suggested in the work of Jobsis and Duffield (1967) (See Review of Literature).

The suggestion is of some interest, for the dimensions of the transform function would be those of Hill's constant, b , which appears in the "characteristic equation" of muscular action (Hill, 1938). That is, the equation $(P + a)V = b(P_0 - P)$ where P is the tension exerted; V , the velocity of contraction; P_0 , the maximum isometric tension of the muscle; and a and b are constants, their units being gm wt and cm sec^{-1} respectively.

The constants a and b were shown to be intimately related to the energetic interchanges occurring in shortening muscle: a is the "shortening heat" per unit length of shortening (Fenn, 1923; 1924; Hill 1938; 1964). b is the ratio of extra energy liberation in shortening to the amount by which the load falls short of the maximum isometric tension of the muscle (Hill, 1938). The units of a are gm wt , those of b , cm sec^{-1} . Hill's equation is fundamental in the description of muscular contraction and can be derived from both mechanical and energy considerations (Hill, 1938).

The question arises of whether the tension-time parameter suggested by Starr can be related to Hill's characteristic equation or to other parameters of muscular performance.

In order to answer the several difficulties posed in this Chapter, it is necessary to find some way to account the mechanical expressions of both dynamic and static action in similar terms which can be related to one another, and to other thermodynamic changes occurring in the activated muscle.

Since measures of impulse have been found to be useful correlates of metabolic effort in isometric muscular action (Hartree and Hill, 1921), the question is posed of whether such measures have validity as correlates of metabolic effort in dynamic work tasks.

The present study therefore investigates:

- i) whether the tension-time unit suggested by Starr is a valid and useful measure of physiological effort in a gross work task
- ii) whether the tension-time and tension-distance integrals are conceptually dependent and able to be inter-related by some transfer function
- iii) whether the gross mechanical and metabolic parameters can be related to thermodynamic interchanges at cellular level, and a definition of muscular efficiency suggested.

CHAPTER II

REVIEW OF LITERATURE

Investigations of the energetic interchanges occurring in muscles during contraction date back to those of Helmholtz (1848), Béclard (1861), and Heidenhain (1864). The simple heat production under different conditions of dynamic and isometric loading was investigated. An account of these early studies has been given by Hill (1959).

The latter two investigators coined the phrase "static work" to describe the metabolic response of muscle stimulated under isometric conditions. Unfortunately the confusing terminology continued in the reports of other investigators (Chauveau, 1896; Lindhard, 1920). As noted earlier, in the present report the term static effort, or isometric effort, will be employed to describe such a response: "work" will be used in the strict physical sense, implying force acting through some distance.

Chauveau (1896) recorded the temperature changes associated with loading the forearm extremity with different weights by means of a thermometer pricked into the skin near the biceps brachii muscle. He found that the force needed to maintain the load statically was proportional to the increase in muscular temperature due to the local metabolic process.

Hartree and Hill (1921) investigated the mechanical expression of tension-time, $\int T.dt$, for isometric contractions of isolated frogs'

muscles. Tension-time was defined as "the area under the isometric tension-time curve, or mathematically as $\int T \cdot dt$ where T is the tension developed and t the time".

For constant temperature and increasing duration of stimulus it was shown that there was a linear relationship between the heat produced and the tension time integral. The authors expressed the opinion that "the tension - time has some real physical (or physiological) significance in the economy of muscle".

In Bronk's (1930) study of the efficiency of isometric muscular action as related to stimulation frequency, the economy or efficiency of performance of isolated frog's muscle was defined as the ratio tension-time: heat production. This formulation may alternatively be expressed as the ratio tension: rate of heat production. It was found that up to a certain stimulation frequency level, the working efficiency increased in direct proportion to the frequency of stimulation. Similar tension-time concepts were used by Bozler (1930), Kamada (1932), and Bronk (1932).

Although investigation of some of the mechanical parameters of human muscles were made by Ralston, Inman, Strait and Shaffrath (1947), and Wilkie (1950), these studies did not investigate the tension-time parameter, nor the energetic interchanges. Indeed, the possible role of the tension-time integral as a determinant of energy metabolism in muscular action has only recently been suggested: it has been pointed out by Mommaerts (1969) that:

... insight has developed that the mere generation of tension and presence of tension itself are associated with an energy dissipation of their own. This seems to have been taken for granted in cardiac physiology, where a tension-time index has become regarded as the principal determinant of metabolism.... In muscle physiology, although considered in passing by Hartree and Hill (75) and implied in Meyerhof's (162) use of an isometric time coefficient, it has played no role whatsoever until recently.

An attempt to fit the tension-time concept into an energy-accounting scheme of gross muscular action was made by Starr (1951). After studying the gross dynamic work of weight-lifting, he suggested that a tension-time integral was a valid measure of metabolic effort: furthermore, he contended that this was applicable to both static and dynamic positive and negative muscular action, so providing a common base of measurement for the assessment of metabolic reaction in all three kinds of muscular effort.

Tension-time was defined as the product of externally-exerted force (dynes) and its time of application (seconds). In the case of constant force, this defines muscular effort simply as the product of force and time. In the case of variable external force, the notion of the tension-time integral, $\int T \cdot dt$ must be invoked. The integral is definite, its limits being the appropriate time limits of force application.

For a weight-lifting task, performed on two separate occasions at different lifting rates, it was shown that the tension-time integral was greater at the faster lifting rate. By the method explained earlier,

(page 8), the tension-time integral for the slower motion was calculated from the adjusted acceleration-time graph to be 1934.5×10^6 dyne sec. For the faster motion the acceleration curve was below the displaced axis between t_1 and t_2 , and between t_3 and t_4 , so the total integral was defined as

$$\int_0^{t_1} m \cdot a' \cdot dt - \int_{t_1}^{t_2} m \cdot a' \cdot dt + \int_{t_2}^{t_3} m \cdot a' \cdot dt - \int_{t_3}^{t_4} m \cdot a' \cdot dt + \int_{t_4}^{2 \text{ sec}} m \cdot a' \cdot dt$$

where a' , the adjusted acceleration, is the vector difference of the observed acceleration, a , and the acceleration of gravity, g . The total integral was then calculated to be 2996.8×10^6 dyne sec.

Because the tension-time integral was shown to be greater at the faster lifting rate, and so correlated with the subjective estimate of necessary effort to perform the tasks, Starr claimed the parameter as a valid measure of physiological effort expended. The opinion was expressed that it "corresponds exactly to the tension time originally defined by Hartree and Hill".

It was implicit in this formulation that tension exerted and rate of metabolic energy consumption were related in a simple way. This notion had already been clearly recognised in the derivation of the "isometric heat coefficient" of isolated muscle. This coefficient is defined by $\frac{P \cdot l_0}{H}$ where P is the tension exerted in an isometric twitch or tetanus; l_0 is the resting length of the muscle; and H is the corresponding heat liberated in the muscle. The coefficient is clearly a

measure of the muscle's economy in tension generation. Many attempts to determine the value of the parameter for different muscles were made, (Hill, 1928; Feng, 1931; Hill, 1931; Rosenberg, 1934; Hill, 1958; Hill and Woledge, 1962).

Direct evidence of the importance of the tension-time integral as a determinant of the energy changes occurring in isotonic contractions was presented by Jobsis and Duffield (1967). It was proposed, from investigations made on isolated muscles of frogs and toads, that energy utilisation was determined by three variables

- i) "the time integral of the developed force", $\int T \cdot dt$
- ii) the time integral of shortening, $\int S \cdot dt$
- iii) the total (external and internal) mechanical work performed, W_T

The total energy expended was thus:

$$\text{Energy used} = K_1 \int T \cdot dt + K_2 \int S \cdot dt + K_3 \cdot W_T$$

These authors pointed out that the parameters $\int T \cdot dt$ and $\int S \cdot dt$ were not in energy units - "these parameters.....are expressed in units that cannot be interconverted at the present time." The units of conversion of the tension-time parameter (i.e. the units of K_1) would clearly need to be those of velocity.

The tension-time integral has found frequent use in cardiac physiology: dependence of cardiac metabolic effort on the tension exerted by the myocardium was claimed on theoretical grounds by Woods (1892), Burch (1955) and Burton (1957). Later, empirical evidence correlating tension-time with myocardial oxygen consumption was

presented by Sarnoff, Braunwald, Welch, Stainsby, Case and Macruz (1958), and Rodbard, Williams and Williams (1959). The importance of this fact in the economy of general function of the heart has been stressed by Starr (1964), Burton (1965), Braunwald (1969) and Banister (1970).

Extensive reviews of the general mechanics and thermodynamics of muscular action have been made by Wilkie, 1954; Podolsky, 1960; Wilkie, 1960; Pringle, 1960; Sandow, 1961; Mommaerts, Brady and Abbott, 1961; Hill, 1965; Lehninger, 1965; Miller, 1968; Mommaerts, 1969; and Banister, 1970. These reviews deal exclusively with the mechanical and energetic phenomena at the microscopic or isolated muscle levels.

Extensive reviews concerning the metabolic energy cost of gross muscular activity have been made by Passmore and Durnin (1955); Durnin and Passmore (1967); Altman and Dittmer (1967); and Banister and Brown (1968). Although the energy costs of activities somewhat similar to bench-stepping have been studied - for example, stair climbing and ladder climbing (Lupton, 1923; Benedict and Parmenter, 1928; Droese, Kofranyi, Kraut and Wildemann, 1949; Orsini and Passmore, 1951; Lehmann, 1953, Hesser, 1965; and Richardson, 1966) - bench-stepping itself has received little attention (Passmore and Thomson, 1950; Mahadeva, Passmore and Wolff, 1953; Banister, 1963). This is perhaps surprising in view of the usefulness of the activity as a standardised work-test in fitness assessment (Brouha, Fradd and Savage, 1944; Kasch, Phillips, Ross and Carter, 1965; Shephard, 1966, 1967).

The diminished energy cost of negative muscular work compared to

positive muscular work has been demonstrated for hill-walking (Chauveau, 1896), treadmill hill-walking (Chauveau, 1901) and cycling (Abbott, Bigland and Ritchie, 1952; Asmussen, 1953; Abbott and Bigland, 1953). The majority of these studies showed that the ratio positive work cost: negative work cost increased as speed of movement increased for equivalent external work loads. Surprisingly, activities such as stepping, which have alternating positive and negative work phases have not been examined in this light.

Similar results have been shown to hold for isolated muscle preparations (Cavagna, Saibene and Margaria, 1965; Baskin and Galluzzi, 1966; Cavagna, Margaria and Dusman 1967; Cavagna, Dusman and Margaria, 1968). The energy cost of true static effort is uninvestigated due perhaps to difficulties caused by masking effects of high inter-individual and intra-individual variability in metabolism (Passmore and Thomson, 1950). Response to static effort has usually been quantified in terms more sensitive than metabolic cost, such as heart rate and blood pressure (Monod, 1956; Tuttle and Howarth, 1957; Hansen and Maggio, 1960; Royce, 1962; Barcroft, Greenwood and Whelan, 1963; Monod and Scherrer, 1964; Koopman, 1965).

The efficiency of muscular work has been investigated for a wide variety of tasks (Henry and De Moor, 1950; Henry 1951; Ronnholm, Karvonen and Lapinleimu, 1962). Optimal work rates for producing maximum efficiency have been demonstrated, particularly in cycle-riding experiments (Hill, 1922; Dickinson, 1929; Garry and Wishart, 1931).

Whipp and Wasserman (1969) have recently attempted to integrate both gross and biochemical interpretations of efficiency, and they found close agreement between the two in a cycle-riding task.

Starr's (1951) technique of using derivatives of distance-time curves has not been described in the current literature. Zajaczkowska (1962) used the second time derivative to calculate mechanical work output in a study concerned with finding the mechanical correlates of skilled performance in weight lifting; no analysis of the method used was attempted however.

In summary, the present state of knowledge about the particular questions which this study investigates is sparse, although a vast general literature exists in related areas. No answer has been made to the questions of Starr (1951) and Banister (1963) about whether the concept of tension-time is a useful or appropriate measure of physiological effort; whether the tension-time integral is meaningful in mechanical work terms; and whether it is related to thermodynamic efficiency. The present study will investigate these questions.

CHAPTER III

METHOD

Subjects and General Design

Four athletic subjects were studied; their ages and weights are given in Table I. Each subject completed four work tasks, stepping at 18, 24, 30 and 36 cycles per minute on separate occasions. (One cycle being a step up and a step down.) The order of assignment of subjects to work tasks satisfied a randomly-chosen 4 x 4 Latin Square design: any practice effect associated with the activity was thus obviated (Winer, 1962). Experiments were done in duplicate to estimate variability in the parameters measured. Figure 1 illustrates the overall experimental design.

TABLE I. Age and weight of subjects

SUBJECT	AGE	WEIGHT RANGE (KG)
MM	21	80.4-82.3
GS	21	78.6-80.3
HK	27	72.5-73.9
RT	28	67.0-68.1

Work Task

The work task used consisted of stepping on and off a bench, 35.7 cm high, at a constant rate for a period of five minutes. This work task was preceded by a five-minute period of cycling on a bicycle

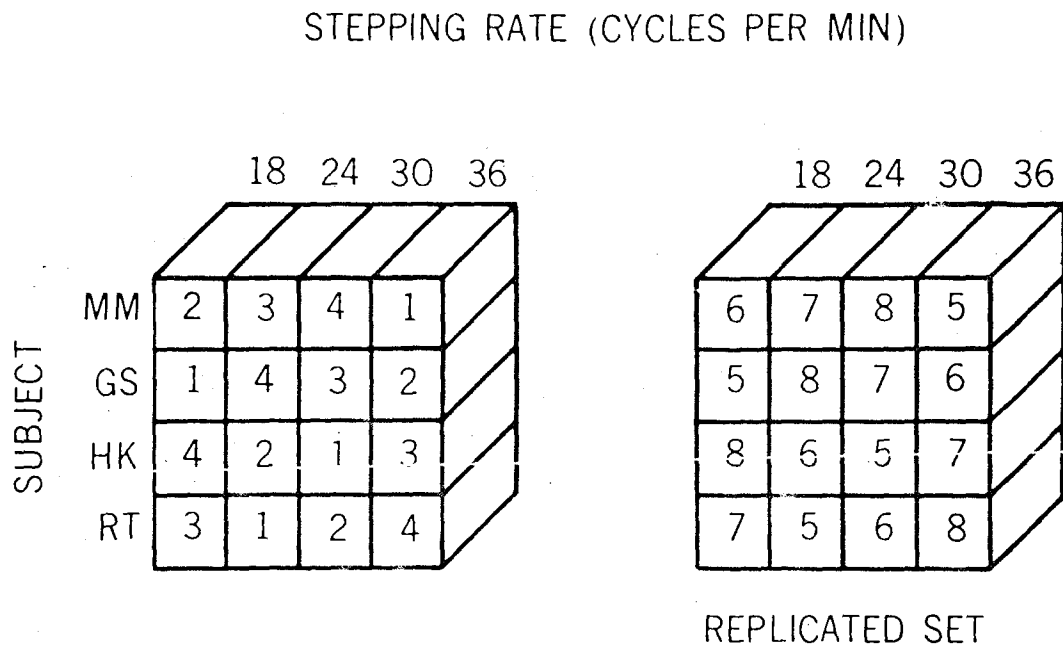


FIG. 1. Diagrammatic representation of experimental design. Numbers in squares indicate the order of administration of work tasks for each subject.

ergometer (von Döbeln; AB Cyclefabriken, Monark, Sweden) at 40 rpm with no load, and followed by a similar five minute period of cycling. Unloaded cycling had less metabolic cost than any stepping task and provided a stable metabolic base-line (Hill, 1965; p. 152).

During stepping, the subject was instructed to use the balls of his feet; the absorption of impact forces by muscular work rather than by the bony structure of the legs was thus ensured. The subject was also instructed to keep arms and hands in a straight line and at a constant angulation to the trunk; to keep the trunk fairly rigid; and to prevent movements of the head relative to the trunk. These latter precautions were necessary to fulfil assumptions made in the mechanical analysis. The stepping rate was set by a metronome.

Throughout the exercise sequence subjects wore only athletic shorts thus allowing precise location of joints during subsequent film analysis. In addition, a one-inch square black marker was attached to the subject's back near the level of the mid-lumbar vertebrae.

Respiratory Gas Collection and Analysis

Throughout the whole of the exercise period the subject exhaled through a Collins low resistance valve connected by non-Kinkable hose ($1\frac{1}{2}$ " ID) to a 5 litre sampling box and a Parkinson-Cowan low-resistance, respiratory gas meter.

The minute volume and temperature of the expired gas was recorded at the end of each minute (Appendix I). During the middle thirty seconds of each minute a sample of expired gas was carefully drawn into

a 50 ml oiled glass syringe as the gas passed through the sampling box.

Expired air samples were analysed for oxygen and carbon dioxide content using a Beckman Model E2 Oxygen analyser, and a Beckman CO₂ analyser calibrated with gases analysed by the Micro-Scholander technique (Scholander, 1947).

The response of the oxygen analyser was linear over the wide range of gas concentrations analysed: the response of the carbon dioxide analyser was curvilinear (Figure 2). A quadratic curve of best fit was then computed to determine carbon dioxide concentrations.

(Appendix 2)

A computer program (Appendix 3) was used for the metabolic calculations (printed example, Figure 3).

Filming

Six film sequences of 15 seconds were taken during the work task. They were taken at the beginning and end of each minute.

The camera was placed 25 feet to the rear of the subject, in the sagittal plane of his body. A mirror, 6 ft x 3 ft, was placed 3 ft to the subject's right and made an angle of 45 degrees with his frontal plane. This allowed the camera to record simultaneously both rear and profile views of the stepping. Artificial lighting ensured good quality film recording.

Two black, horizontal strips of tape were attached to a wall, facing, and in the visual field of the camera. They were so placed as to be visible above the head of the subject. Their purpose was to serve

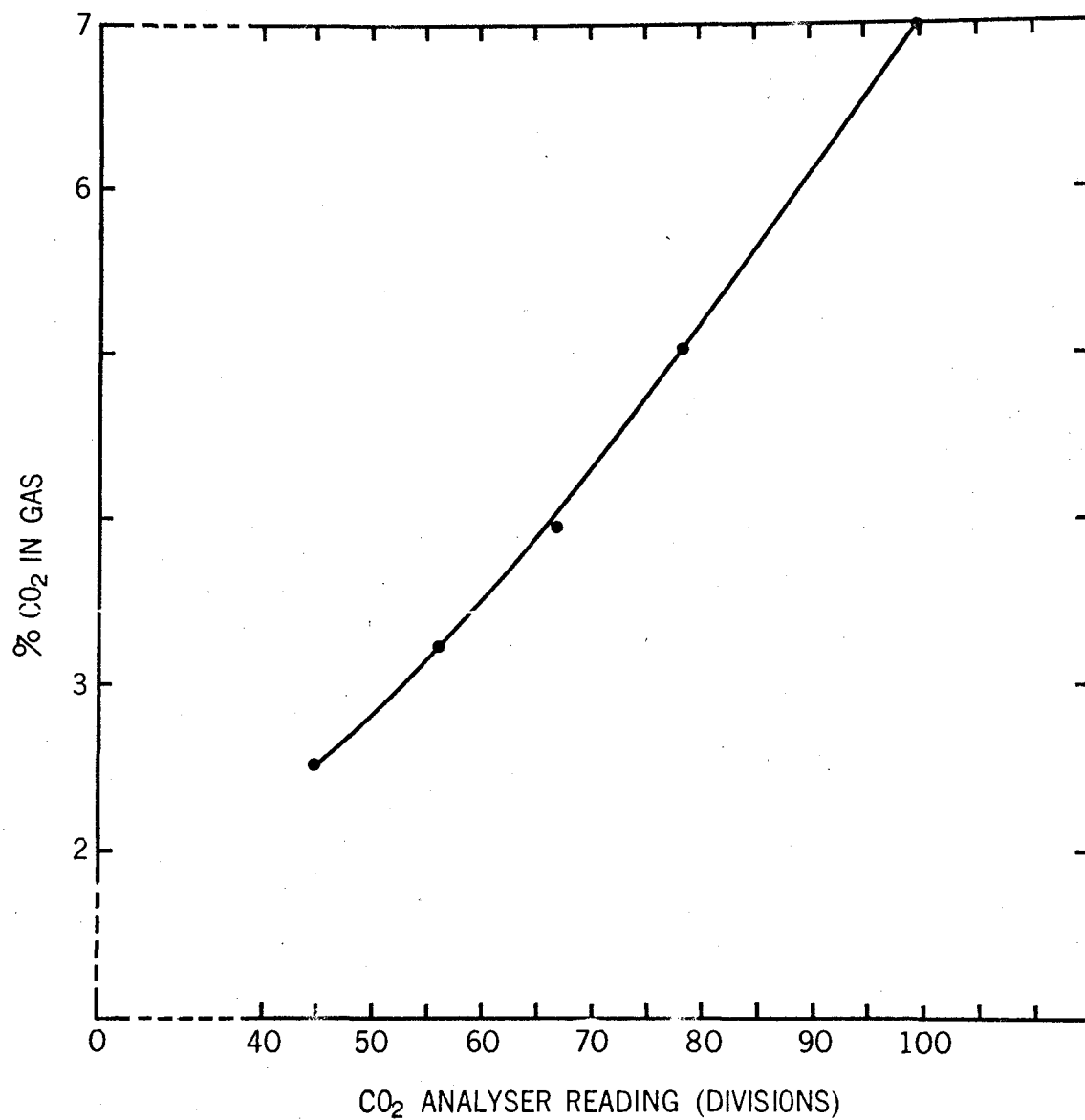


FIG. 2. Instrument response curve for carbon dioxide analyser. Equation of curve computed to be: $\%CO_2 = 0.000336(CO_2 \text{ Reading})^2 + 0.03379(CO_2 \text{ Reading}) + 0.264$

OXYGEN UPTAKE DETERMINATION

SUBJECT: M MASON DATE: 05MAY69 WT: 80.4 KG SRATE: 24 ANAL: 2.3 A

MINUTE	* V' AIR ATPS *	* MEAN TEMP *	* V' AIR STPD *
1	12.700	21.000	11.201
2	13.500	21.000	11.906
3	13.100	21.000	11.553
4	12.300	21.000	10.848
5	13.500	21.000	11.906
6	31.700	21.250	27.923
7	50.700	21.750	44.547
8	56.400	22.250	49.429
9	59.200	22.750	51.751
10	63.700	23.000	55.613
11	45.300	23.150	39.518
12	28.800	23.150	25.124
13	23.500	22.900	20.527
14	19.700	22.800	17.217
15	17.900	22.800	15.644

% O2	* % CO2 *	* % N2 *	* RER *	* VO2 USED *
16.250	4.076	79.674	0.8	0.547
16.350	3.803	79.847	0.8	0.575
16.500	3.726	79.774	0.8	0.539
16.150	4.115	79.735	0.8	0.543
16.600	3.651	79.749	0.8	0.542
15.550	4.646	79.804	0.8	1.569
15.100	4.987	79.913	0.8	2.717
15.350	5.118	79.532	0.9	2.841
15.550	4.987	79.463	0.9	2.862
15.550	4.987	79.463	0.9	3.075
16.050	4.773	79.177	1.0	1.958
16.850	4.398	78.752	1.1	1.015
17.200	3.841	78.959	1.0	0.769
17.150	3.764	79.085	1.0	0.659
17.100	3.628	79.272	0.9	0.615

FIG. 3. Computer output calculation of gross oxygen uptake for each minute of unloaded cycling, stepping, and recovery unloaded cycling from respiratory data.

as horizontal and vertical alignment checks in subsequent film analysis.

A calibration scale 200 cm in length, clearly marked by black strips at 25 cm intervals was placed vertically near the foot of the bench (on the camera side). It was visible to the camera both directly and by reflection in the mirror. A board recording the name of the subject, and the stepping rate used was held in the visual field of the camera. Prior to exercise the calibration and appropriate identification data was filmed.

Analysis of Film Data

The distance-time relation of the movement of the subject's centre of gravity throughout a complete stepping cycle was obtained.

From each of 32 film records, one complete step cycle was selected. The sequence contained between 36 and 72 frames, depending on the step rate.

The position of the subject's centre of gravity on every frame was determined by use of a Vanguard Motion Analyser (Vanguard Instrument Corporation, New York). The location of this point was first determined with reference to the coordinates of the Analyser.

The body can be considered as a jointed system of rigid members (Figure 4). Each member can be considered as having its weight concentrated at its centre of gravity; or, alternatively it may be considered as having its weight proportionately distributed at each of its ends.

If we consider a simple system of two members AB and BC, jointed at

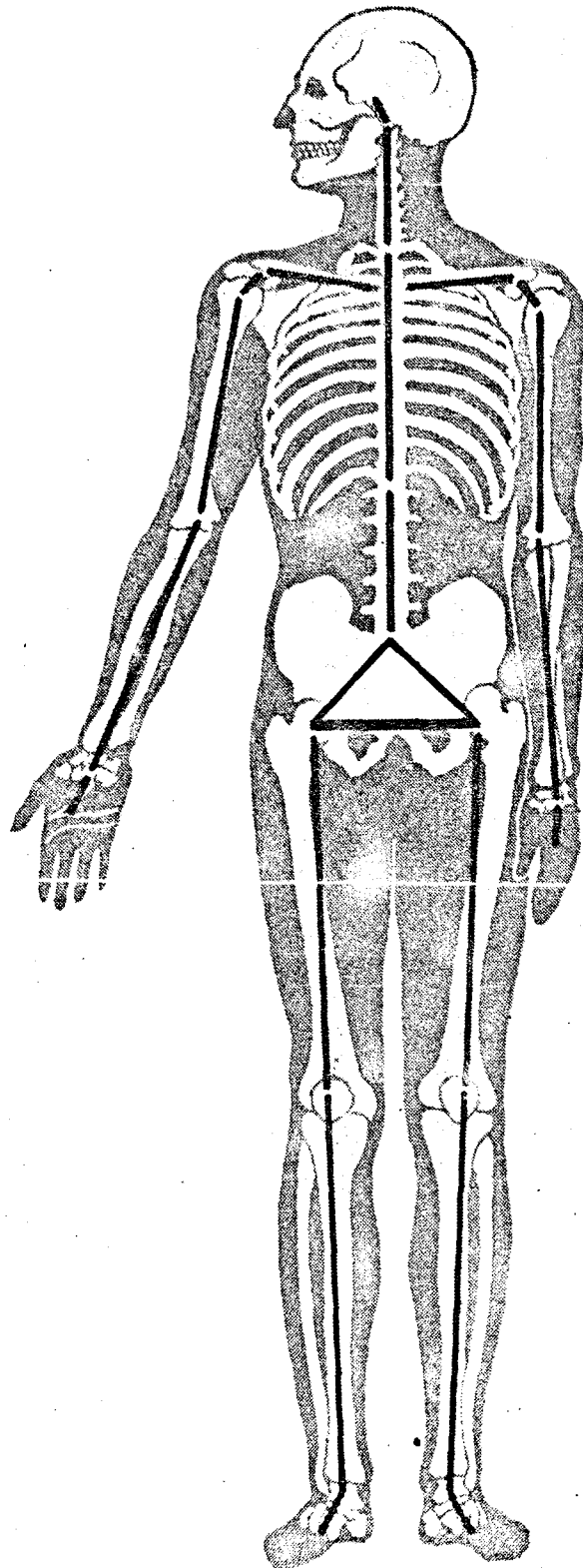


FIG. 4. The body as a jointed system of rods
(from Dempster, 1955b).

B, and of weight m_1 and m_2 , the centre of gravity of each member is situated at G' and G'' respectively such that the ratios $AG': AB$, and $BG'': BC$ are equal to s and t .

The two member system may be either considered composed of weights m_1 and m_2 situated at G' and G'' respectively: or, of weights $m_1 \cdot (1-s)$; $m_1 s + m_2 \cdot (1-t)$; and $m_2 t$ situated at A, B and C respectively: or, again, it may also be considered composed of weights m_1 , $m_2 \cdot (1-t)$, and $m_2 t$, situated at G' , B, and C respectively.

If the Cartesian coordinates of each of the points A, B, C, G' and G'' are known then the centre of gravity of the entire system can be calculated as the sum of the products of proportionate weight and coordinate values associated with each point, divided by the total weight of the system. For example, for the latter system, if the coordinates of G' , B and C are respectively $(X_{G'}, Y_{G'})$, (X_B, Y_B) , and (X_C, Y_C) , then the X and Y coordinates of the centre of gravity of the system are:-

$$X \text{ coordinate} = \frac{m_1 \cdot X_{G'} + m_2 (1-t) \cdot X_B + m_2 \cdot t \cdot X_C}{(m_1 + m_2)}$$

$$Y \text{ coordinate} = \frac{m_1 \cdot Y_{G'} + m_2 (1-t) \cdot Y_B + m_2 \cdot t \cdot Y_C}{(m_1 + m_2)}$$

All three methods of system analysis yield the same overall body centre of gravity. In the present analysis, the whole-body centre of gravity was determined as in the last analysis described above.

The body was considered composed of seven rigid members: i) head, upper limb, trunk and abdomen (one unit) ii) right thigh iii) left thigh iv) right shank v) left shank vi) right foot vii) left foot. The weight of each of these seven members was calculated from body-weight distribution data of Dempster (1955a). Slight adjustments accounted for the weight of the headpiece and mask worn by the subject. The adjusted weight distribution is shown in Table II.

TABLE II. Showing the weight of rigid members of the body as a percentage of total body weight. (a) from Dempster, 1955a (b) adjusted to account for weight of a headpiece (0.6Kg) worn by subjects

	%Weight (a)	%Weight (b)
Body	68.8	69.6
Thigh (one)	9.7	9.453
Shank (one)	4.5	4.384
Foot (one)	1.4	1.368

The reference points of the multi-member system were chosen as: the black marker placed in the mid-lumbar region ('spot marker'); the centre of the right acetabular joint; the centres of the knee and ankle joints of each leg; and the estimated centre of gravity of each foot.

Dempster (1955a) found empirically that the centre of gravity of all three rigid members of the lower limb (thigh, shank and foot) was

located 47 per cent of the segment length from the proximal joint of the segment. (Figure 5). This fact was used to calculate the weight factors associated with each of the eight chosen reference points in the manner described previously. The resulting weight factors are shown in Table III.

TABLE III. Weight factors associated with 5 reference points.

Reference Point	Weight Factor
Spot	69.60
Hip	10.82
Knee	6.53
Ankle	1.89
Foot	1.37

The coordinates of each of the reference points (in the coordinate system of the Motion Analyser), were found by consecutively bringing the intersection of the vertical and horizontal crosswires of the instrument into coincidence with each reference point. The coordinates of the spot marker were taken from the frontal-plane photograph. Coordinates of the other seven reference points were ascertained from the profile, sagittal plane photograph seen as the mirror image. Measurements taken in the frontal plane were termed Scale 1 measures; those taken in the sagittal plane, Scale 2 measures (Appendix 4).

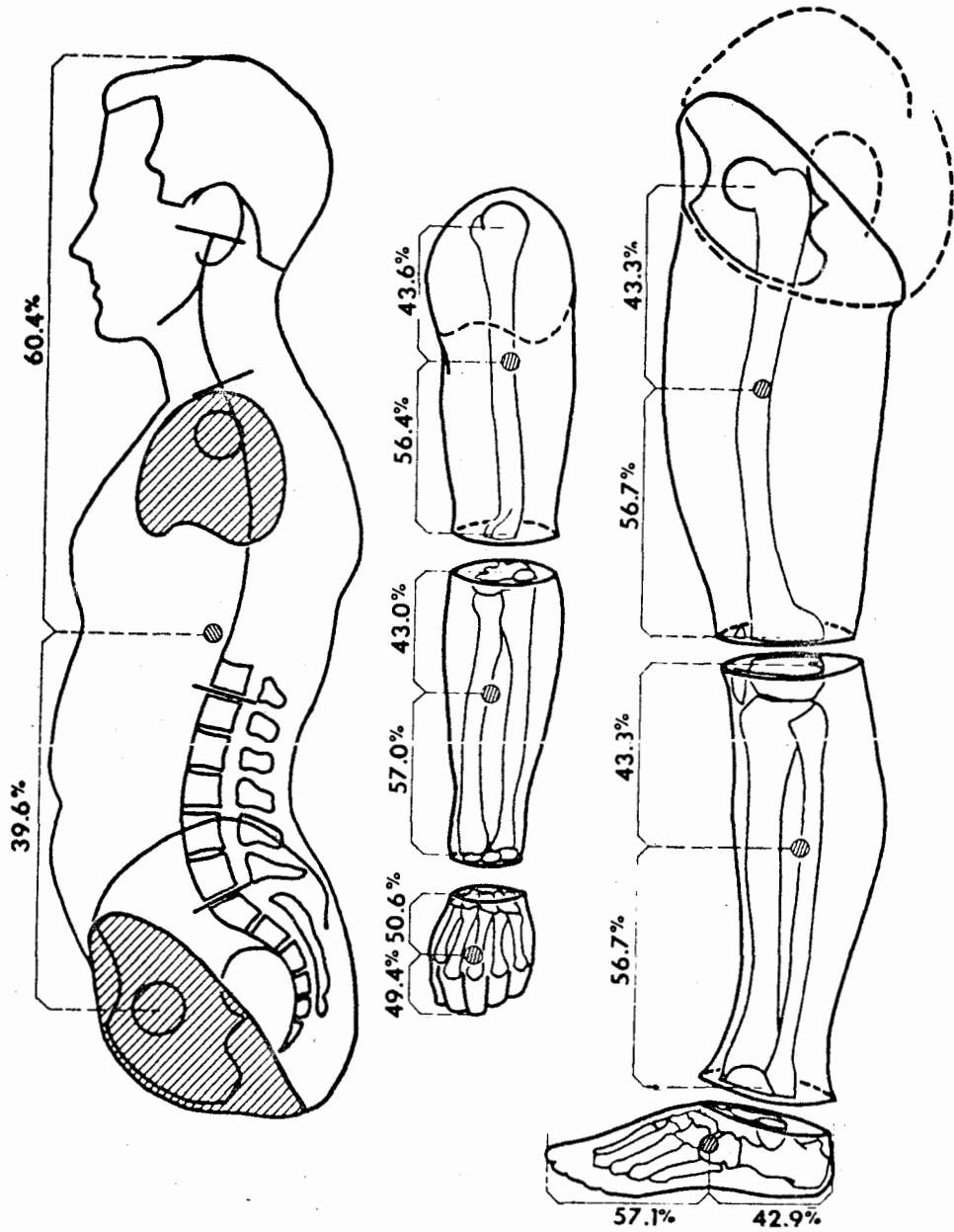


FIG. 5. Location of centres of gravity of the body segments relative to segment length (from Dempster, 1961).

Summation of the products of proportional weight factors and coordinates of each reference point divided by 100 (the total weight of the system as a percentage), indicated the location of the virtual centre of gravity. This procedure, repeated for each successive frame of the film, traced the movement of the virtual centre of gravity.

It must be noted that the 'virtual' centre of gravity is not the real centre of gravity. It is a point whose vertical and horizontal movements follow those of the real centre of gravity. The reason that the real centre of gravity cannot be located is that the arbitrarily-placed spot marker is not coincident with the centre of gravity of the head - upper limbs - thorax - abdomen unit. The distinction is unimportant in practice since only changes in the centre of gravity position are important, not its absolute position. These changes are identical for both the real and virtual centre of gravity if an assumption is made that the spot marker shares the same vertical and horizontal movement as the centre of gravity of the upper-body complex. The latter requires that the several parts of the upper-body unit do not move relative to one another. Precautions were taken to ensure this and the assumption was considered valid. It is for this reason that the distinction between 'real' and 'virtual' centre of gravity is unimportant and 'centre of gravity' is therefore used without distinction.

A second assumption simplifying the analysis is that the acetabular axis did not skew appreciably from its initial alignment when the subject stood at rest in front of the bench. It follows from this assumption

that the sagittal-plane, horizontal and vertical coordinates of both acetabular joints are the same. Thus the coordinates of only one hip joint are needed: the present experimental arrangement made it most convenient to choose the right acetabular joint.

Conversion of the measurements from the photographic analyser to 'real space' measurements was effected from the relation of film analyser readings corresponding to 25 cm intervals of a 2 metre rule filmed beside the step bench, and the image of these intervals in the mirror.

The following graphical relationships were examined:

- a) Scale 1 readings: Scale 2 readings
- b) Scale 1 readings: Real Space Readings
- c) Scale 2 readings: Real Space Readings

Relationship (a) was clearly linear. Relationships (b) and (c) were slightly curvilinear. (This was due to an obliquity phenomenon, caused by points off the optical axis of the camera lens being further away than axial points). Quadratic equations were fitted to the relationships (b) and (c) using a Gaussian least-squares solution.

A computer program (Appendix 5) performed all calculations, and the complete real distance-time curves of vertical and horizontal movement of the centre of gravity were determined (Figures 6 and 7).

Timing of the step sequence was determined from the film speed. The internal calibration of the camera (accurate to 1% at 24 frames per second) was checked by filming a high speed clock.

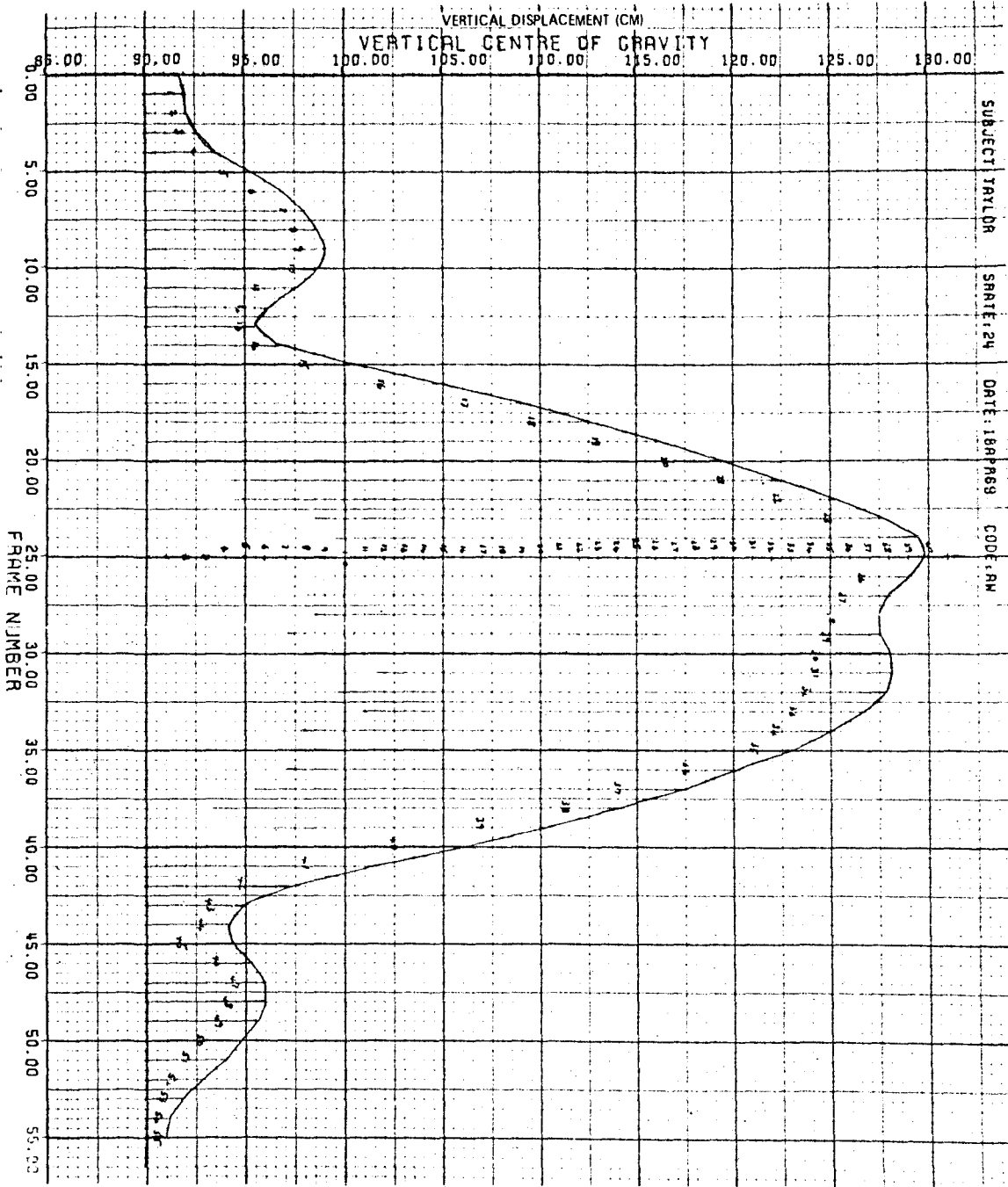


FIG. 6. A computer-plotted distance-time curve of vertical movements of centre of gravity, in bench stepping. Hand-drawn smoothing of the curve is shown.

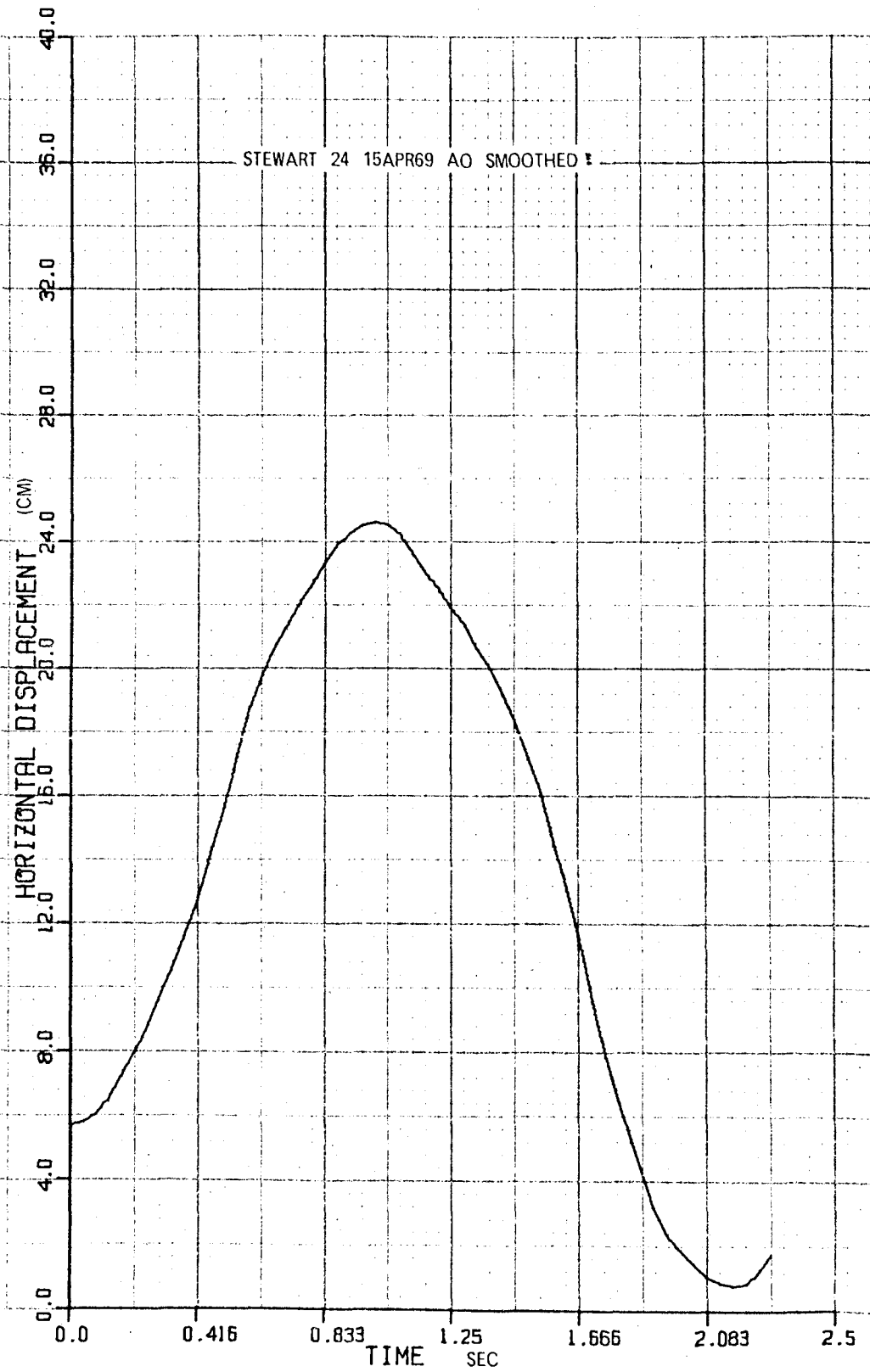


FIG. 7. A computer-plotted distance-time curve of horizontal movements of the centre of gravity in bench stepping.

From distance - time curves of centre of gravity movements, corresponding velocity-time and acceleration-time graphs were derived by a computer program using numerical differentiation (Appendix 6). These graphs were computer plotted and typical examples are shown in Figures 8, 9, 10 and 11. The general forms of the curves for vertical movement are shown diagrammatically in Figure 12.

The abscissal axis of the acceleration-time graph was displaced - $|g|$ acceleration units, in the manner adopted by Starr (1951), and an adjusted acceleration-time graph obtained. By substituting distance, from the original distance-time curve, for the independent time variable of the adjusted acceleration-time curve, an adjusted acceleration-distance curve was drawn. General forms of these curves are shown in Figure 13.

Force-time integrals were calculated as the product of the area beneath selected parts of the adjusted acceleration-time curve and the mass of the subject ($m \int_{lims} a' . dt$, where $a' = a + |g|$). Similarly, force-distance integrals were calculated as the product of the area beneath selected parts of the adjusted acceleration-distance curve and the mass of the subject ($m \int_{lims} a' . ds$). To discriminate selected parts of the curves points were defined on the original distance-time graph at and between which activity was described as follows:

- 0 Starting point of cycle
- 0-1 Period during which the leading leg is raised and placed onto the bench.
- 1 Time at which the up-step of the whole body begins: defined from the distance-time curve as the first minimum of the curve: this was not clearly defined in all cases.

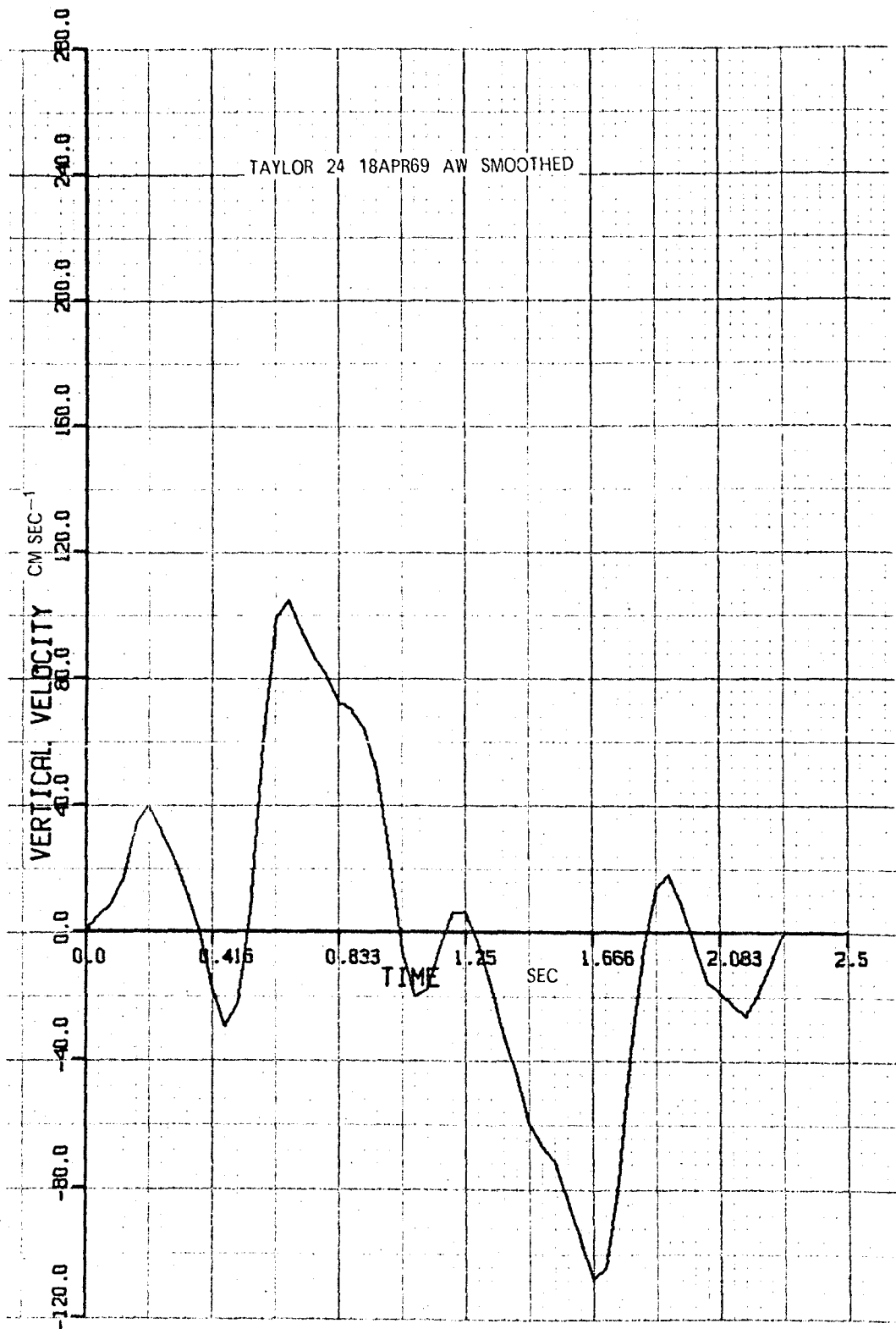


FIG. 8. A computer-plotted velocity-time curve of vertical movements of the centre of gravity in bench stepping.

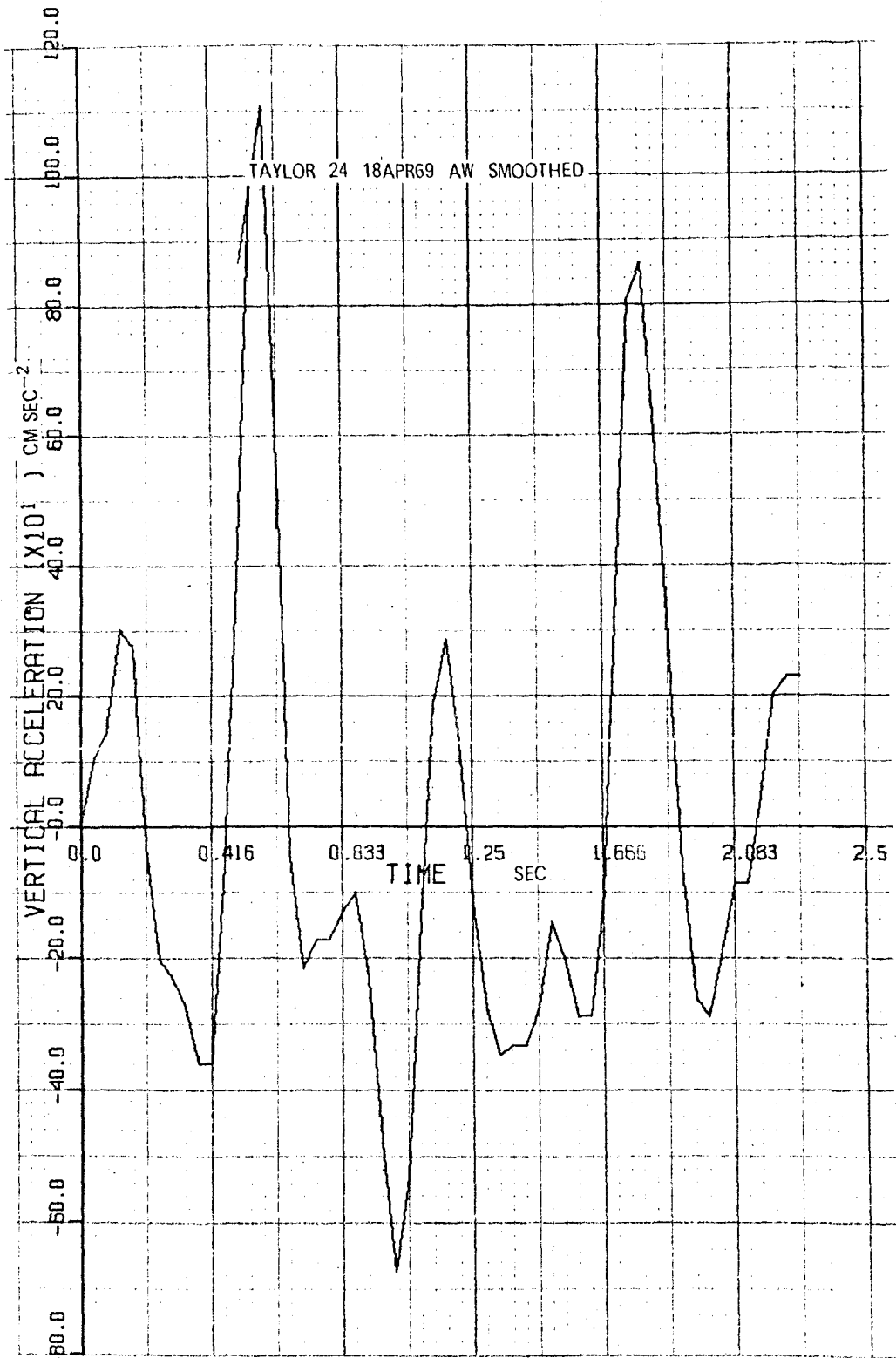


FIG. 9. A computer-plotted acceleration-time curve of vertical movements of the centre of gravity in bench stepping.

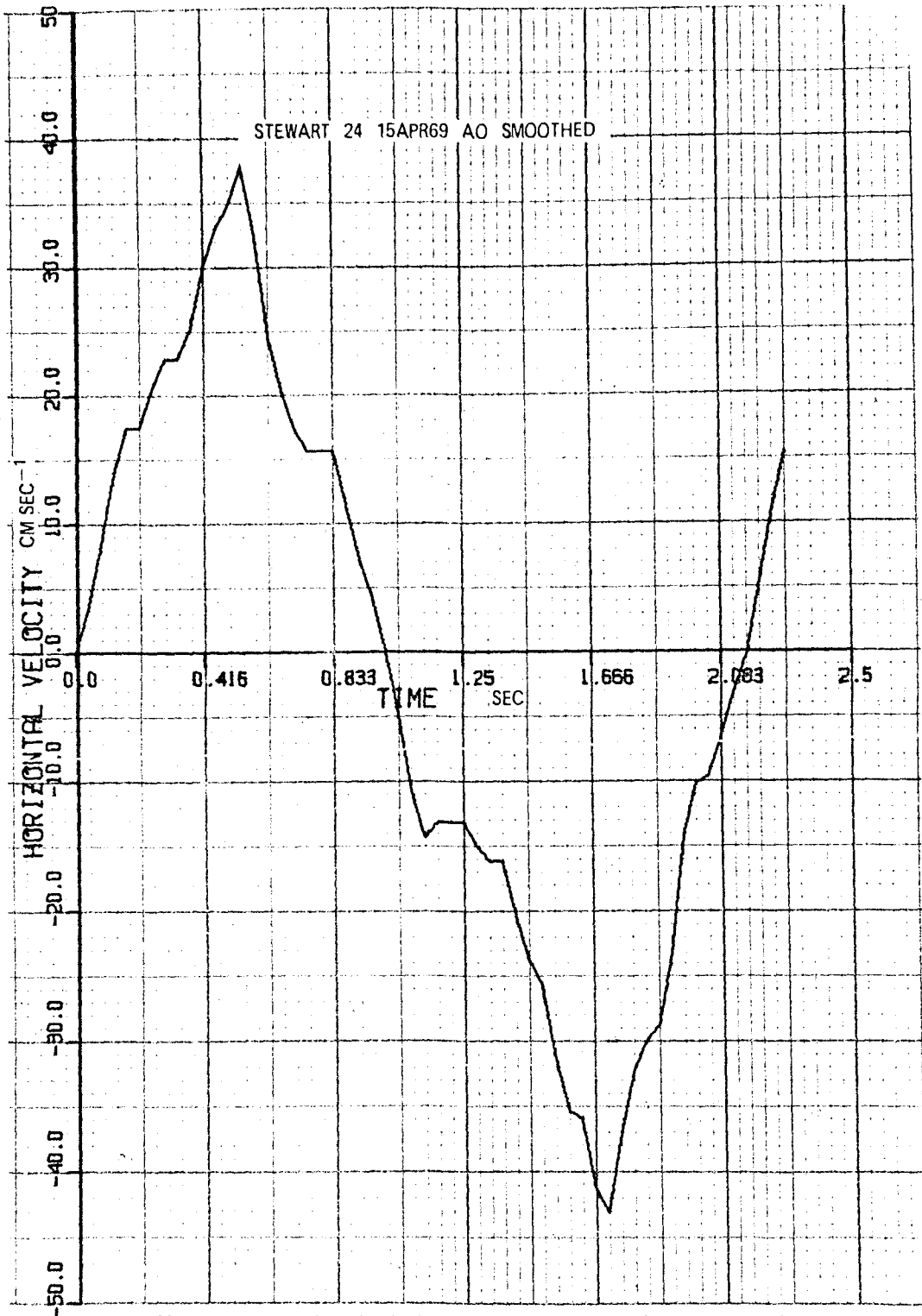


FIG. 10. A computer-plotted velocity-time curve of horizontal movements of the centre of gravity in bench stepping

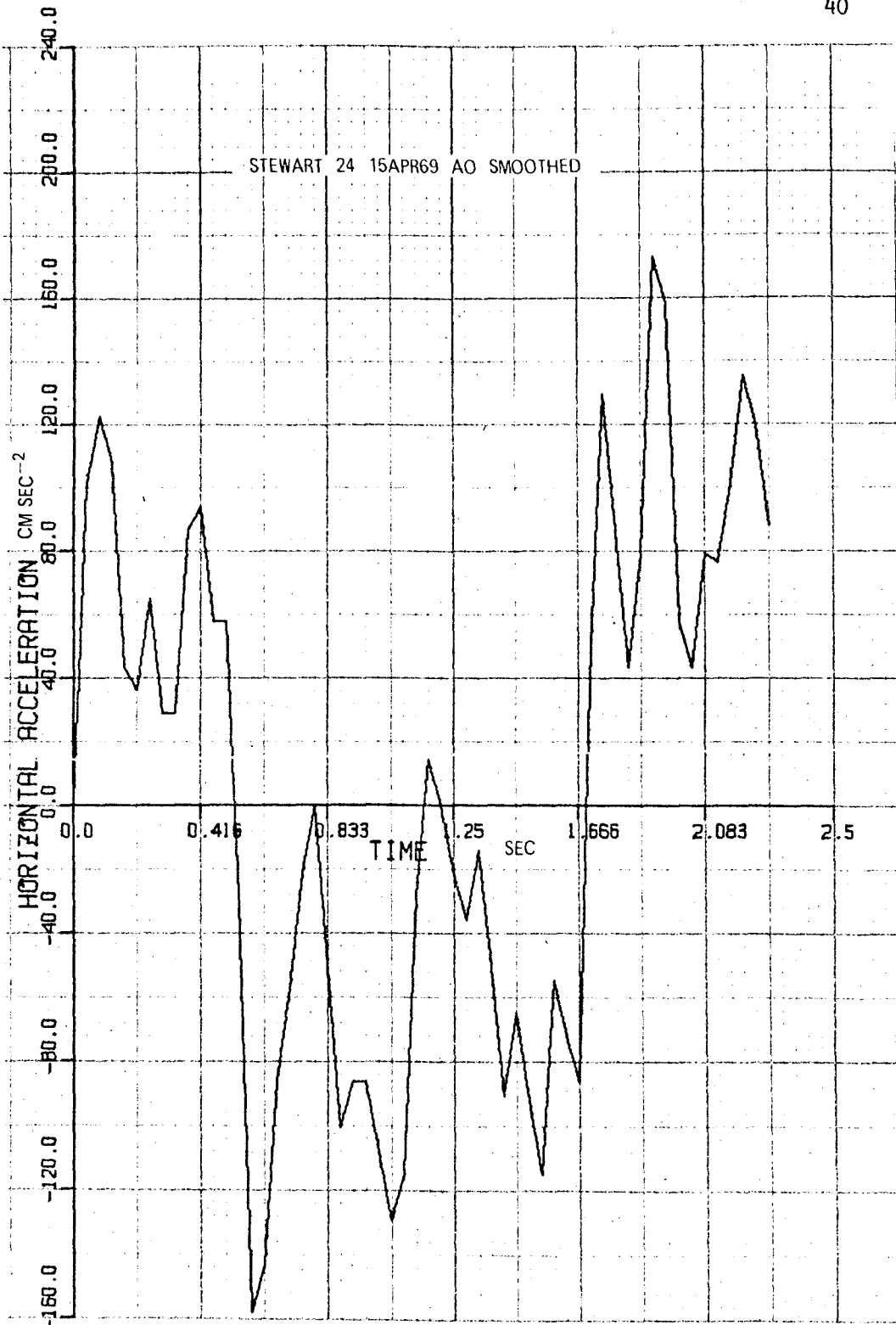


FIG. 11. A computer-plotted acceleration-time curve of horizontal movements of the centre of gravity in bench stepping.

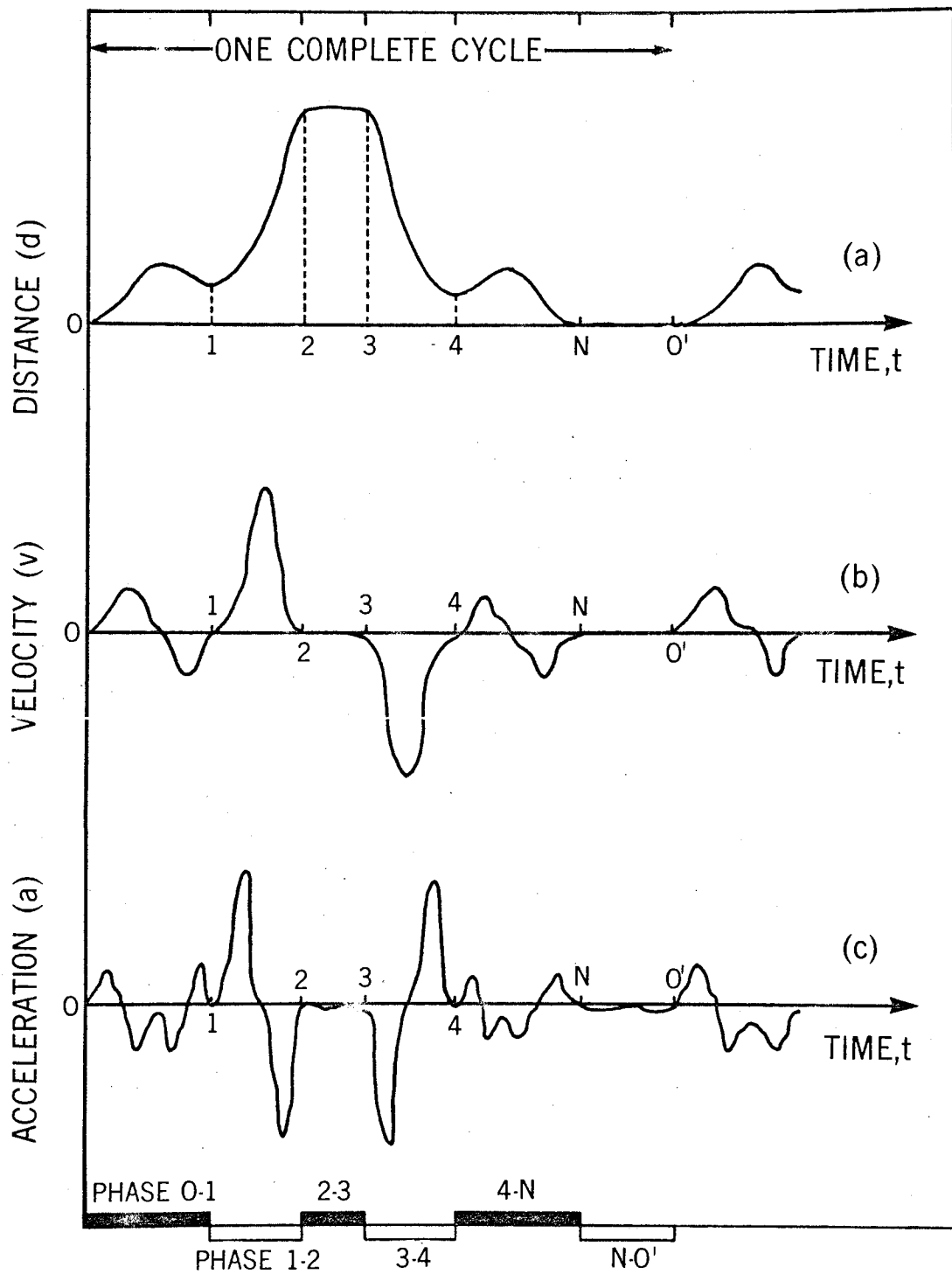


FIG. 12. General forms of (a) distance-time (b) velocity-time and (c) acceleration-time curves for vertical movements of the whole-body centre of gravity.

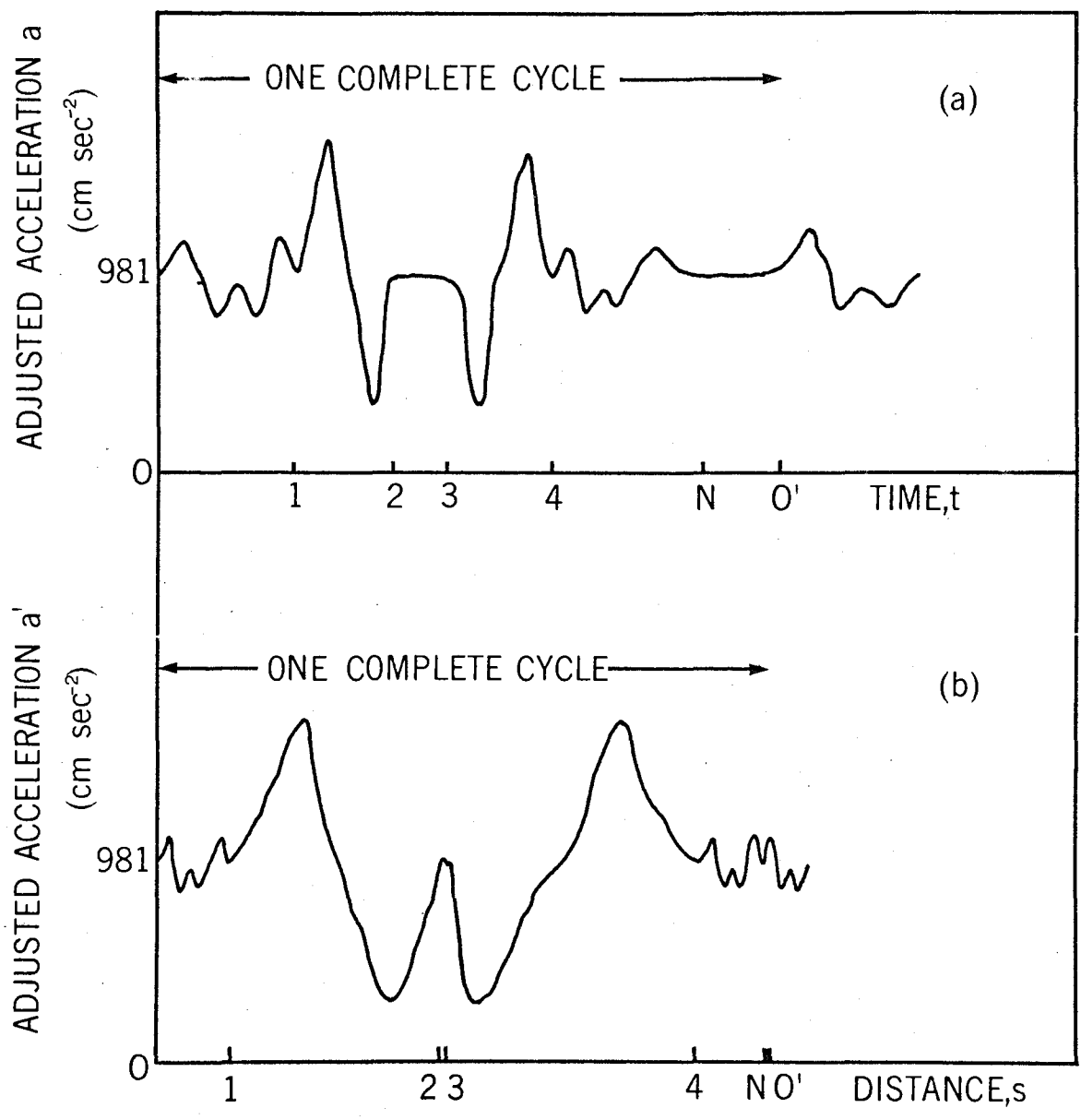


FIG. 13. General forms of (a) adjusted acceleration-time curve and (b) adjusted acceleration-distance curve for vertical movements of the whole-body centre of gravity.

- 1-2 Period of up-rise of the whole body.
- 2 Time at which the centre of gravity becomes relatively stationary at its highest point.
- 2-3 Period during which the centre of gravity remains relatively stationary at its highest point.
- 3 Time at which the whole body descent begins.
- 3-4 Period of descent of whole body.
- 4 First minimum on the descent phase; coincides with time at which the leading leg begins to leave the bench.
- 4-N Period of bringing the lead leg back to the ground.
- N End point of cycle: subject in standing position on the floor.
- N-0' Period of standing on the floor.
- 0' Starting point of next cycle.

(Figure 12)

The areas under various parts of the curves are then defined as:

T_{112} = adjusted acceleration-time integral 1-2: the area under the adjusted acceleration-time curve between the integral limits specified by time 1 and time 2 (as defined above)

Similarly T_{123} and T_{134} .

S_{112} = adjusted acceleration-distance integral 1-2, the area under the adjusted acceleration-time curve between the integral limits specified by time 1 and time 2 (as defined above)

Similarly S_{101} , S_{123} , S_{134} and S_{14N} .

These areas and the average velocity of movement during phases 1-2 and 3-4 were computed (program, Appendix 6) and printed (example, Figure 14). Average velocities are denoted V_{AV12} and V_{AV34} in the ascending and descending phases of the cycle respectively.

TAYLOR 24 18APR69		AW SMOOTHED	
MASS = 67.20 KG.			
CALCULATIONS		VERTICAL RESULTS	HORIZONTAL RESULTS
INTEGRALS OF ADJUSTED ACCN.			
		ABS(ACCN.+G) VS T UNITS ARE CM/SEC	ABS(ACCN) VS T
FROM T1 TO T2 = TI12		0.4602661E 03	0.4379999E 02
FROM T2 TO T3 = TI23		0.2582329E 03	0.2879977E 02
FROM T3 TO T4 = TI34		0.5263333E 03	0.4470001E 02
		ABS(ACCN.+G) VS S UNITS ARE (CM/SEC)**2	ABS(ACCN) VS S
FROM 0 TO S1 = SI01		0.1074014E 05	0.5889597E 03
FROM S1 TO S2 = SI12		0.3357978E 05	0.1423439E 04
FROM S2 TO S3 = SI23		0.2726866E 04	0.2030385E 03
FROM S3 TO S4 = SI34		0.3329753E 05	0.1434952E 04
FROM S4 TO END= SI4N		0.6728016E 04	0.5515142E 03
RATIOS OF INTEGRALS		UNITS ARE CM/SEC	
SI12/TI12 = R12		0.7295731E 02	0.3249860E 02
SI34/TI34 = R34		0.6326320E 02	0.3210182E 02
AV OF R12,R34 = RAV		0.6776529E 02	0.3229898E 02
MEAN VELOCITY CALCULATIONS		UNITS ARE (CM/SFC)	
(S2-S1)/(T2-T1) = VAV12		0.7396356E 02	0.3141817E 02
(S3-S4)/(T4-T3) = VAV34		0.6258455E 02	0.2879990E 02
AV OF VAV12,VAV34 = VAV		0.6779990E 02	0.3005209E 02
MECHANICAL WORK EXPRESSIONS		UNITS ARE KCAL	
FROM S1 TO S2			
(MASS*SI12) = W12		0.5372762E-01	0.2277501E-02
FROM S3 TO S4			
(MASS*SI34) = W34		0.5327603E-01	0.2295923E-02
FROM S2 TO S3 (POSS.1)			
(MASS*SI23) = W23P1		0.4362982E-02	0.3248614E-03
TOTAL WORK (POSS.1)			
(MASS* (SI01+SI4N) +W12+W34+W23P1) = WTOT1		0.1393156E 00	0.6723035E-02

FIG. 14. Computer output calculation of mechanical parameters for one step-cycle.

CHAPTER IV

RESULTS

Metabolic Analysis

Table IV summarises the analysis of the oxygen consumption. The mean value of two experiments for each subject at each stepping rate is shown: intra-individual variability is indicated by the mean difference (averaged over all experiments) between the two values and shown at the foot of each column.

Metabolic data for the experiments at 36 steps per minute are not shown: technical difficulties made the respiratory data collected at high step rates unreliable.

The oxygen cost of performing a physical activity is usually measured from a fixed baseline level of oxygen consumption. Whipp and Wassermann (1969) used a baseline of "unloaded pedalling" on a bicycle ergometer (60 rpm): in the present study the resting level of oxygen consumption was chosen as a baseline (0.350 litres per minute, Whipp and Wassermann, 1969). For comparative purposes, however, both a resting consumption baseline and an unloaded pedalling baseline (40 rpm) were used in subsequent calculations.

Two methods of calculating the minute oxygen cost of the stepping exercise above a baseline were also used:

Method 1: adding total exercise and recovery oxygen consumption;
subtracting ten times the minute consumption associated

TABLE IV. Showing gross oxygen uptake during unloaded cycling, bench stepping (at 3 rates) and recovery for 4 subjects. Each value shown is the mean of values from two experiments. Values at foot of each column shown the mean difference between values for the two experiments averaged over all experiments.

Subject	Step Rate cycle ⁻¹ min ⁻¹	VO ₂ 5 mins		VO ₂ 5 mins		VO ₂ 5 mins		Steady State VO ₂ litre min ⁻¹
		Cycling litre	Stepping litre	Recovery litre	Recovery litre	Recovery litre		
MM	30	3.088	16.277	6.199				3.384
GS	30	3.753	16.963	6.365				3.950
HK	30	3.415	15.777	6.293				3.670
RT	30	2.814	14.212	5.300				3.231
MM	24	2.989	12.847	4.975				2.985
GS	24	3.320	14.128	6.092				3.198
HK	24	3.058	12.199	4.776				2.833
RT	24	2.892	12.252	4.362				2.770
MM	18	3.367	10.349	4.610				2.363
GS	18	3.370	11.308	5.551				2.433
HK	18	2.632	8.986	4.204				2.158
RT	18	2.486	8.175	3.555				1.903
		0.387	0.536	0.383				0.173

with the appropriate "baseline" activity (total exercise and recovery time was 10 minutes); and dividing the resulting value by 10, gives the appropriate minute oxygen consumption of stepping.

Method 2: taking the steady-state minute oxygen consumption during stepping (the maximum $\dot{V}O_2$ reached was in all cases suitable for taking as the steady-state value), and subtracting the minute consumption of the baseline activity.

Table V summarises calculations of the minute oxygen cost of stepping by Method 1, using unloaded pedalling as baseline, and by Method 2 using both unloaded pedalling and resting as baseline. Both methods using unloaded cycling as baseline yield very similar results, the average difference in the minute oxygen cost of stepping being less than 0.1 litres per minute.

Using Method 2, and resting oxygen consumption as baseline, the calculated minute oxygen cost of stepping averages approximately 0.3 litres per minute higher at all stepping rates than when calculated by the other methods.

Although the metabolic cost of stepping (litres of oxygen per minute) varies over a fairly wide range between subjects (ranges 2.88 - 3.60, 2.42 - 2.85, and 1.55 - 2.08 at stepping rates 30, 24, and 18 cycles per minute respectively for the latter-mentioned method of calculation), the metabolic cost expressed in ml oxygen per kg of body weight (Table V) remains within a narrow range at all stepping rates (respectively 42.6 - 45.2, 32.4 - 36.0, and 22.9 - 26.3).

Mechanical Analysis

The distance-time curve of the centre of gravity during vertical movement shows three maxima and two minima turning points (Figure 12, page 41). The movement phases associated with particular parts of the curve were defined earlier (page 36). From the distance-time curve the film frame number corresponding to each of the reference points 0, 1, 2, 3, 4, N and 0' were noted and the durations of each of the phases 0-1, 1-2, 2-3, 3-4, and 4-N, determined (Table VI).

From distance-time data, the average velocity of vertical movement in the up-phase (1-2) and down-phase (3-4) of each cycle was calculated by computer and denoted VAV₁₂ and VAV₃₄ respectively. Velocities of horizontal movement were calculated similarly (Table VII).

Adjusted acceleration-time integrals for vertical and horizontal movement were calculated by computer (Figure 14, page 44) for phases 1-2, 2-3, and 3-4, and respectively denoted T₁₁₂, T₁₂₃, and T₁₃₄. These integrals were summated to yield phase 1-4 adjusted acceleration-time integrals (Table VIII). Tension-time integrals could be obtained from the adjusted acceleration-time integrals by multiplying by the mass.

Adjusted acceleration-distance integrals for vertical and horizontal movement were calculated (Figure 14) for phases 0-1, 1-2, 2-3, 3-4, and 4-N and denoted S₁₀₁, S₁₁₂, S₁₂₃, S₁₃₄, and S_{14N} respectively.

The ratios of the adjusted acceleration-distance and adjusted acceleration-time integrals for phases 1-2 and 3-4 (respectively $R_{12} = S_{112}/T_{112}$, and $R_{34} = S_{134}/T_{134}$) were determined for both horizontal and vertical movement (Figure 14). Values for all experiments are summarised in Table IX.

TABLE VI. Showing duration of the phases of the step cycle described in Figure 12 (page 41) at different step rates for 4 subjects. Duration is expressed in Frame Intervals, where 1 frame interval equals 1/24 second.

SUBJECT	STEP RATE cycle ⁻¹ min ⁻¹	PHASE DURATION					
		0-1	1-2	2-3	3-4	4-N	N-0'
MM	36	7	13	1	12	6	1
MM	36	8	12	1	12	6	1
GS	36	7	12	1	13	6	1
GS	36	7	12	0	11	8	2
HK	36	6	13	1	13	6	1
HK	36	9	10	0	14	5	2
RT	36	5	9	0	14	6	6
RT	36	8	12	0	15	5	0
MM	30	11	12	1	13	8	3
MM	30	9	14	1	13	7	4
GS	30	9	12	1	15	8	3
GS	30	10	13	0	13	8	4
HK	30	9	12	2	15	7	3
HK	30	8	13	1	13	10	3
RT	30	10	11	5	11	9	2
RT	30	10	10	1	16	7	4
MM	24	12	14	1	16	10	7
MM	24	14	12	7	12	11	4
GS	24	12	10	9	13	12	4
GS	24	12	13	4	14	11	6
HK	24	12	16	1	17	11	3
HK	24	11	14	1	20	10	4
RT	24	13	11	6	12	12	6
RT	24	14	11	7	13	11	4
MM	18	15	16	8	17	14	10
MM	18	15	15	6	15	13	6
GS	18	15	17	9	14	15	10
GS	18	12	17	8	18	16	9
HK	18	14	19	3	21	14	9
HK	18	16	16	7	15	16	10
RT	18	15	18	2	20	16	9
RT	18	16	15	7	16	14	12

TABLE VII. Showing average vertical and horizontal velocity of rise-up (VAV12) and lower-down (VAV34) of whole body in stepping, for 4 subjects at 4 stepping rates.

SUBJECT	STEP RATE cycle ⁻¹ min ⁻¹	VERTICAL VELOCITY (cm sec ⁻¹)		HORIZONTAL VELOCITY (cm sec ⁻¹)	
		VAV12	VAV34	VAV12	VAV34
MM	36	45.2	56.0	25.9	21.6
MM	36	52.8	61.6	18.6	23.8
GS	36	55.4	62.4	19.8	19.9
GS	36	53.8	69.6	20.6	30.7
HK	36	59.3	60.7	28.1	17.2
HK	36	81.0	60.0	17.1	18.9
RT	36	69.9	76.5	21.2	26.2
RT	36	64.0	55.2	20.0	21.6
MM	30	65.6	58.7	23.6	22.3
MM	30	47.8	59.7	14.8	24.1
GS	30	62.2	60.8	20.6	28.0
GS	30	53.9	64.4	19.6	20.5
HK	30	64.4	56.3	22.4	21.8
HK	30	56.5	61.7	21.2	22.3
RT	30	73.1	70.9	24.2	23.7
RT	30	81.1	53.0	21.1	19.3
MM	24	46.1	48.9	20.1	21.1
MM	24	60.5	66.5	15.4	27.1
GS	24	71.4	68.3	23.8	28.1
GS	24	53.4	59.1	18.7	25.9
HK	24	44.0	44.6	19.7	15.4
HK	24	55.7	40.3	16.3	14.0
RT	24	60.9	54.4	31.4	30.6
RT	24	74.0	62.6	31.4	28.8
MM	18	44.8	49.8	19.4	18.7
MM	18	49.4	57.9	20.6	25.0
GS	18	39.0	53.3	19.9	24.3
GS	18	38.9	43.9	20.4	19.1
HK	18	38.8	38.4	15.7	17.6
HK	18	49.1	54.2	21.6	20.6
RT	18	43.7	45.5	21.3	25.9
RT	18	52.6	53.0	22.7	21.4

TABLE VIII. Adjusted acceleration-time integrals for vertical movement during phases 1-2 (T112), 2-3 (T123), 3-4 (T134), and 1-4 (T114) for 4 subjects at 4 stepping rates.

SUBJECT	STEP RATE cycle ⁻¹ min ⁻¹	$\int a' \cdot dt$ (cm sec ⁻¹)			
		T112	T123	T134	T114
MM	36	513	27	506	1046
MM	36	493	25	494	1012
GS	36	465	26	537	1028
GS	36	481	0	379	860
HK	36	544	12	520	1076
HK	36	380	0	564	944
RT	36	328	0	467	795
RT	36	476	0	606	1082
MM	30	492	25	524	1041
MM	30	573	21	557	1151
GS	30	486	22	623	1131
GS	30	514	0	536	1050
HK	30	500	55	612	1167
HK	30	521	25	485	1031
RT	30	434	195	446	1075
RT	30	408	14	654	1076
MM	24	553	37	659	1249
MM	24	470	272	483	1225
GS	24	404	339	540	1283
GS	24	505	152	578	1235
HK	24	645	35	692	1372
HK	24	574	29	815	1418
RT	24	452	229	444	1125
RT	24	460	258	526	1244
MM	18	641	319	706	1666
MM	18	600	241	598	1439
GS	18	693	365	544	1602
GS	18	703	326	697	1726
HK	18	744	113	863	1750
HK	18	666	272	586	1524
RT	18	718	73	825	1616
RT	18	606	277	653	1536

TABLE IX. Showing integral ratios between the time limits of each phase ($\lims_{a'.ds}$: $\lims_{a'.dt}$) for step-cycle phases 1-2 (R12), and 3-4 (R34), for vertical and horizontal whole-body movement. Units of R are cm sec^{-1} .

SUBJECT	STEP RATE $\text{cycle}^{-1} \text{min}^{-1}$	VERTICAL MOVEMENT		HORIZONTAL MOVEMENT	
		R12	R34	R12	R34
MM	36	46.5	54.3	25.9	21.6
MM	36	52.5	61.1	18.6	23.8
GS	36	57.4	61.7	19.8	19.9
GS	36	53.5	79.6	20.6	30.7
HK	36	57.6	61.6	28.1	17.2
HK	36	86.5	60.2	17.1	18.9
RT	36	68.6	86.3	21.2	26.2
RT	36	65.8	55.5	20.0	21.6
MM	30	65.6	59.7	23.6	22.3
MM	30	47.6	57.1	14.8	24.1
GS	30	62.4	59.9	20.6	28.0
GS	30	55.5	63.7	19.6	20.5
HK	30	63.1	56.4	22.4	21.8
HK	30	57.0	65.5	21.2	22.3
RT	30	75.5	71.5	24.2	23.7
RT	30	81.6	52.7	21.1	19.3
MM	24	47.5	48.5	20.1	21.1
MM	24	63.2	67.8	15.4	27.1
GS	24	73.0	67.6	23.8	28.1
GS	24	56.3	58.4	18.7	25.9
HK	24	44.5	44.7	19.7	15.4
HK	24	55.4	40.3	16.3	14.0
RT	24	60.5	58.0	31.4	30.6
RT	24	73.0	63.3	31.4	28.8
MM	18	45.6	49.3	19.4	18.7
MM	18	50.7	59.6	20.6	25.0
GS	18	39.0	55.8	19.9	24.3
GS	18	38.5	45.8	20.4	19.1
HK	18	38.8	38.2	15.7	17.6
HK	18	48.3	56.2	21.6	20.6
RT	18	45.0	45.2	21.3	25.9
RT	18	53.1	53.1	22.7	21.4

To ascertain the effect of deviations of the original distance-time data from a smooth form on the values of the computed integrals, the distance-time curve was smoothed and new 'smoothed' distance-time values read from it. (Figures 6 and 7). Both 'smoothed' and 'unsmoothed' distance-time data were used to calculate adjusted acceleration-time and adjusted acceleration-distance integrals and integral ratios. The effect of curve-smoothing on obtained values for the integrals was negligible.

The mechanical work associated with vertical and horizontal movements of the body is shown in Table X. These values are calculated by multiplying corresponding adjusted acceleration-distance integrals, $\int_0^N a' \cdot ds$, by the body mass (Figure 14). The mechanical work done was also simply calculated as 2 x body weight x bench height (Table X). Slight differences in theoretical values for the same subject on different occasions were caused by variations in body weight.

TABLE X. Showing mechanical work done per step by 4 subjects at 4 step rates calculated (a) from adjusted acceleration-distance integral $\int_0^N a' \cdot ds$ for vertical movement (b) from acceleration-distance integral $\int_0^N a \cdot ds$ for horizontal movement, and (c) from 2 x weight of subject x bench height for vertical movement.

SUBJECT	STEP RATE cycle ⁻¹ min ⁻¹	MECHANICAL WORK (CAL) PER STEP		
		(a)	(b)	(c)
MM	36	120	6.8	138
MM	36	127	6.0	136
GS	36	134	6.6	132
GS	36	129	8.9	132
HK	36	121	6.3	122
HK	36	127	4.9	123
RT	36	140	5.9	113
RT	36	117	5.2	114
MM	30	146	6.1	136
MM	30	131	5.2	135
GS	30	155	7.4	133
GS	30	142	5.4	135
HK	30	131	5.9	124
HK	30	128	6.2	124
RT	30	132	4.2	112
RT	30	123	4.3	114
MM	24	144	4.8	137
MM	24	154	5.1	135
GS	24	175	6.1	133
GS	24	148	5.5	134
HK	24	125	3.4	124
HK	24	131	3.0	123
RT	24	122	7.5	112
RT	24	139	6.7	113
MM	18	157	3.9	138
MM	18	162	5.2	135
GS	18	145	4.8	133
GS	18	143	5.0	133
HK	18	127	3.4	124
HK	18	133	4.2	123
RT	18	140	6.7	112
RT	18	133	3.4	114

CHAPTER V

INTERPRETATIONS OF RESULTS AND DISCUSSION

In order to answer clearly the specific questions posed in Chapter I, the quantitative nature of stepping is first described since the present analysis has found several distinct features of interest and importance.

Quantitative Analysis of Stepping

Bench stepping consists of two phases of double-stance, one on the floor and the other on the bench. These are separated by two single-stance phases (when the free leg swings to a new position) and two double stance phases when one foot is on the bench and the other on the floor. The relation of these to the reference phases 0-1, 1-2, 2-3, 3-4, 4-N and N-0' is illustrated in Figure 12.

It was found that as stepping rate increased each of the phase durations did not decrease in proportionate or interdependent manner (Table XI). Instead, subjects adapted to faster stepping rates primarily by shortening the time spent standing on the bench or floor. Table XI shows that phase durations N-0' and 2-3 (respectively floor standing and bench-top standing) decreased disproportionately more than the other phase durations; phase durations 1-2 and 3-4 (respectively up-rise and lower-down of whole body) decreased less than proportionately expected; phase durations 0-1 and 4-N (respectively leading-leg-raise and leading-leg-lower) decreased in a

TABLE XI. Expected phase durations at step rates above 18 cycles per min assuming proportionate decrement in phase duration with rate. Average actually-observed values are shown in parentheses. Durations are in arbitrary units of $\frac{1}{8 \times 24}$ sec.

	Phase	0-1	1-2	2-3	3-4	4-N	N-0'	0-0'
Step Rate								
18		118 (118)	133 (133)	50 (50)	136 (136)	118 (118)	85 (85)	640
24		89 (100)	100 (101)	38 (36)	102 (117)	89 (88)	64 (38)	480
30		71 (76)	80 (97)	30 (12)	82 (109)	71 (64)	51 (26)	384
36		59 (57)	67 (93)	25 (4)	68 (104)	59 (49)	43 (13)	320

proportionate manner. These results are illustrated graphically in Figures 15 and 16.

The stability of the duration of the up- and down-step phases (1-2 and 3-4) is also illustrated by the average *c* of *g* velocities at different stepping rates. The median velocities of upward movement were 57.4, 63.3, 58.1 and 44.3 cm per sec at 36, 30, 24, and 18 cycles per minute respectively (Figure 17): corresponding median *c* of *g* velocities for downward movement were 61.2, 60.3, 56.8 and 51.4 cm per sec respectively (Figure 18).

Although these median values show little significant change with increased stepping rate, consideration of the whole set of mean velocity-of-movement values suggests a slightly increasing trend as stepping rate increases (Figures 17 and 18). Inter- and intra-individual variability in these measurements masks precise relations but the general trend is clear; increased stepping rate leads to only slight increases in movement velocity, instead, adjustment in the overall step-cycle time is made by greater-than-proportionate shortening of the stationary phases of the cycle. This seems at first inconsistent with the previous finding that the durations of phases 1-2 and 3-4 do decrease, if only slightly. However, it is noted that this is compensated for by the fact that the body does not rise fully when stepping rate increases (shown by decrease in mechanical work done per step in the vertical direction as stepping rate increases, Table X).

The distance moved is less and the average velocity, defined by the distance:time ratio, remains more or less constant.

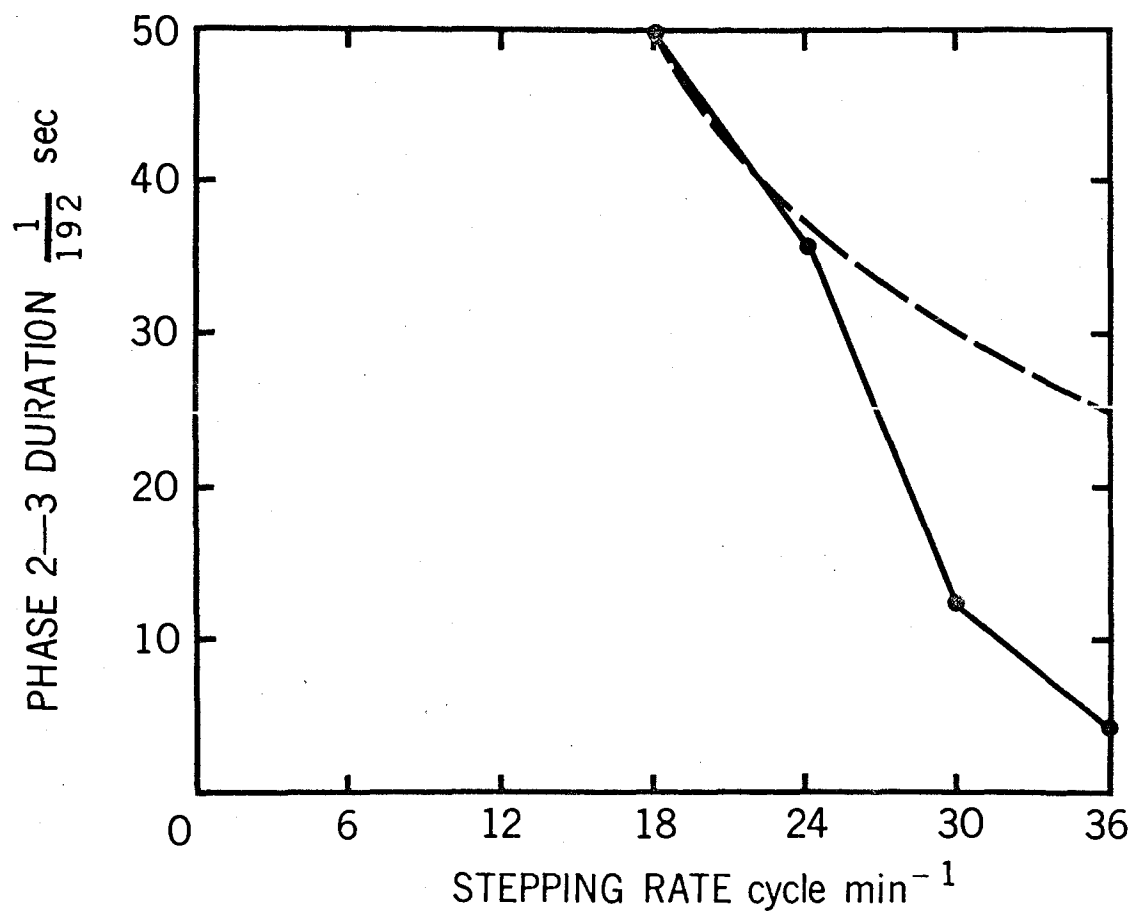


FIG. 15. Showing how the duration of the stationary phase on the bench (phase 2-3) decreases more (solid line) than that expected if all phases decreased proportionately (broken line) in response to increased step rate.

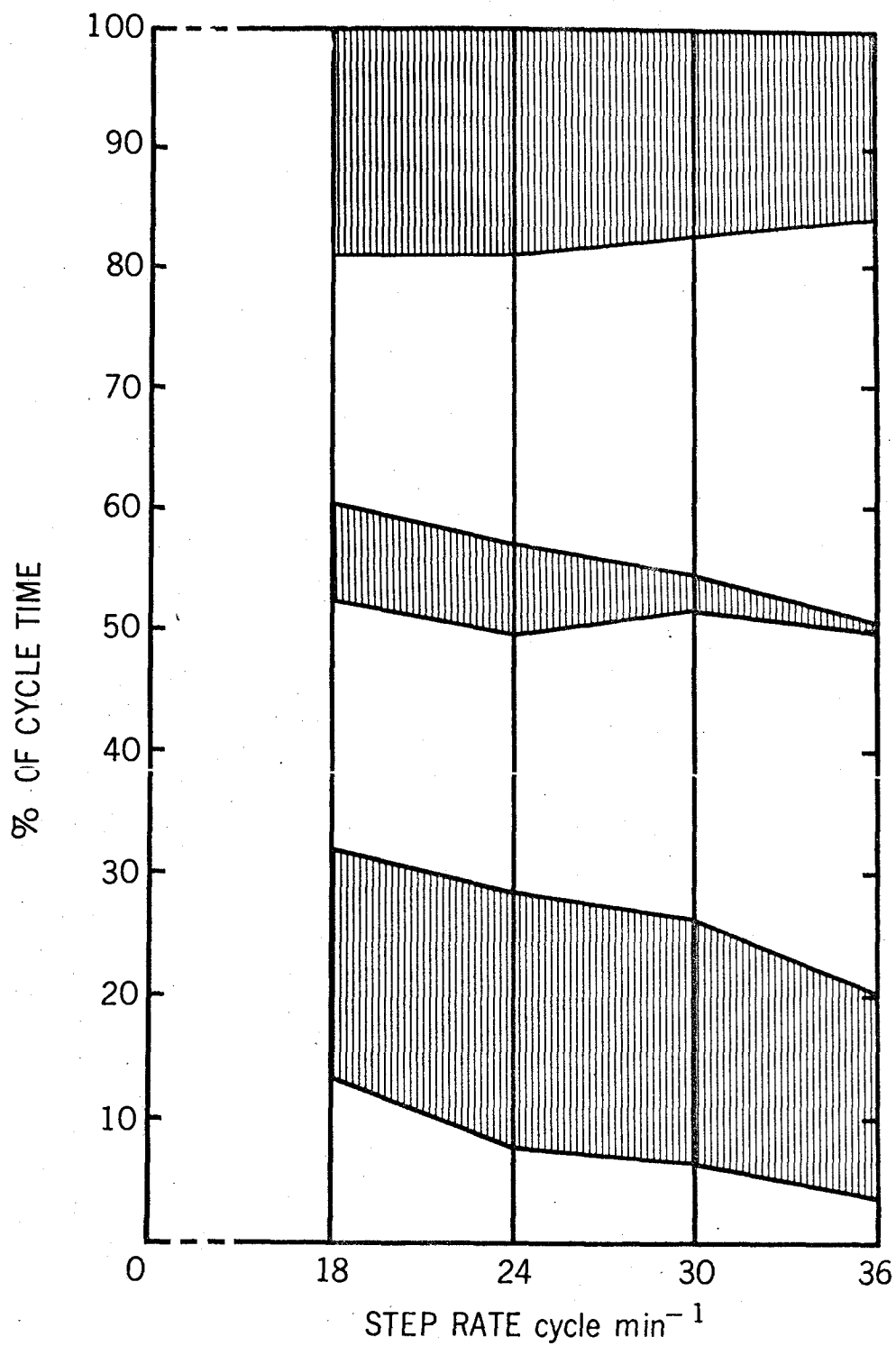


FIG. 16. Time spent in defined phases of the step cycle at 4 step rates as a percentage of total cycle time. Bottom to top: — Phases N-0', 0-1, 1-2, 2-3, 3-4, and 4-N respectively.

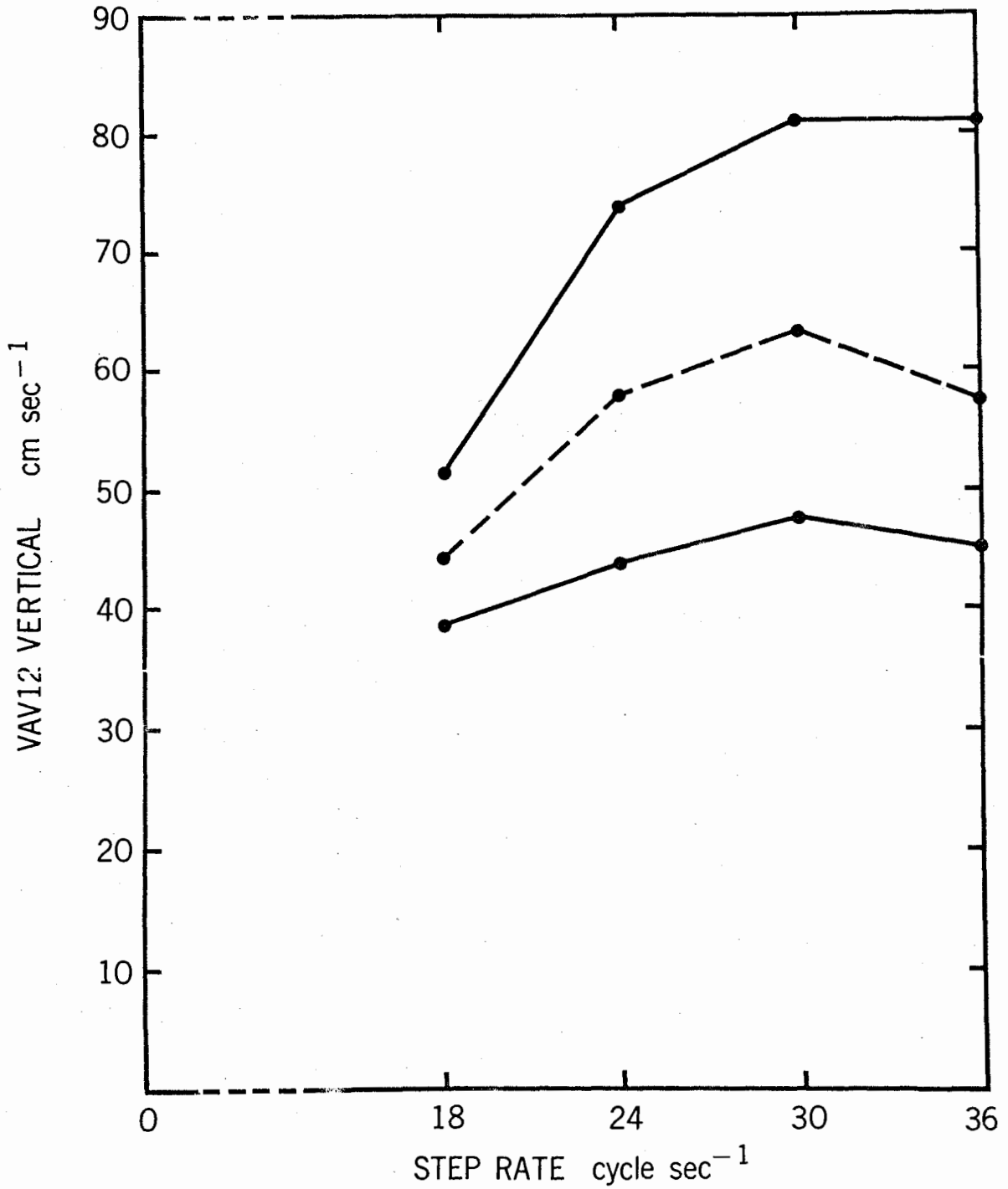


FIG. 17. Showing the range (solid line) and median (broken line) of 8 values of the average vertical velocity of the whole-body C of G during step phase 1-2, for 4 subjects at 4 step rates.

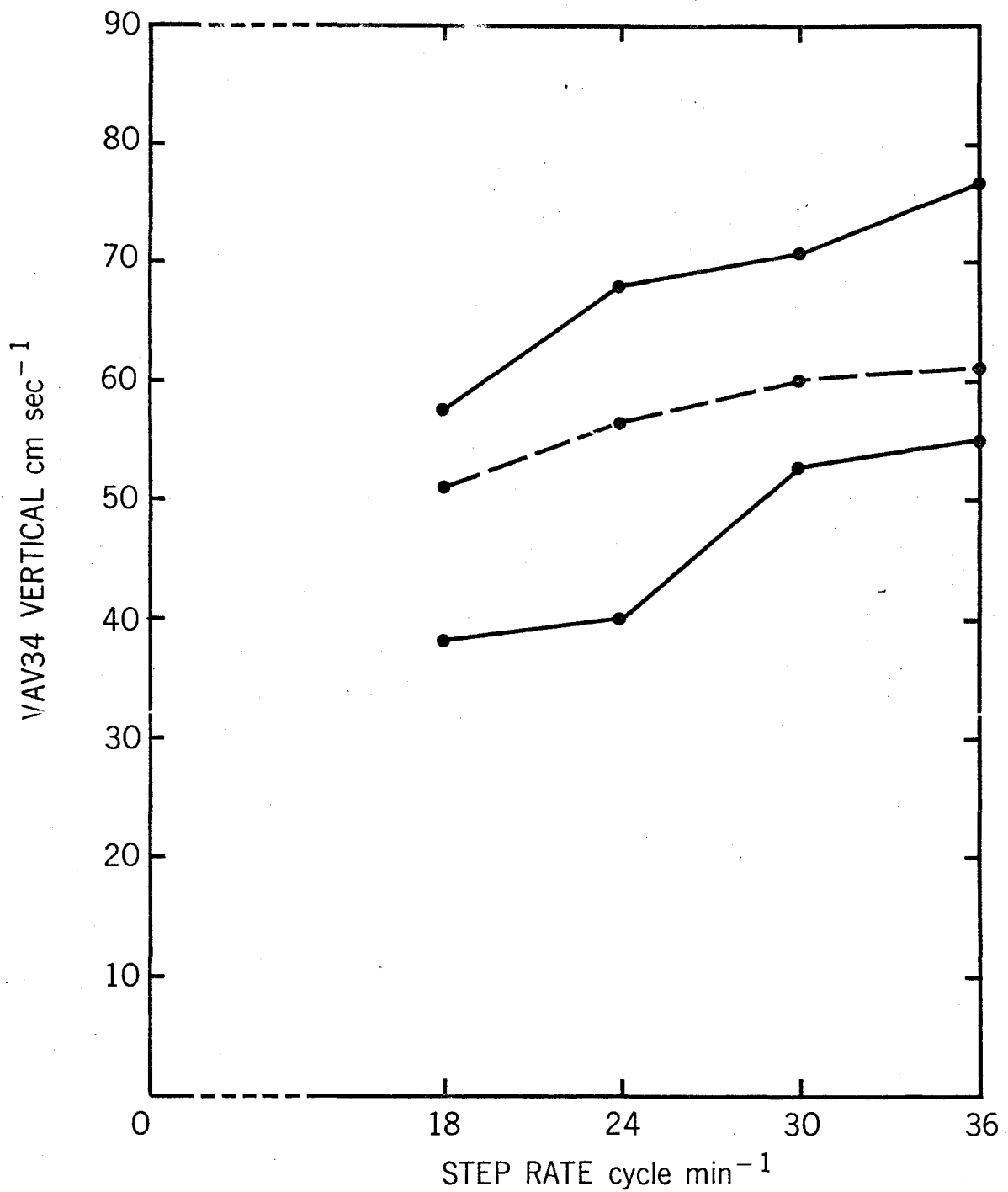


FIG. 18. Showing the range (solid lines) and median (broken line) of 8 values of the average vertical velocity of the whole-body C of G during step phase 3-4, for 4 subjects at 4 step rates.

It is interesting to note that a similar phenomenon to the above has been observed in the phase-duration adaptations to increased walking speed (Contini, Gage and Drillis, 1965; Murray, Kory and Clarkson, 1966).

It is noted, too, from the median c of g movement velocity values, that no significant difference is apparent between the velocities of upward and downward movement; in other words, the external work rate is the same in both positive and negative work phases.

Adjustments of horizontal velocity in response to increased stepping rate were similarly considered. Median c of g average velocity values were 20.3, 20.3, 19.9 and 20.5 cm per sec for forward movement (Figure 19), and 21.6, 22.3, 26.5, and 21.0 cm per sec for backward movement (Figure 20) at 36, 30, 24 and 18 cycles per min respectively. There are no significant differences in these values, and consideration of the whole range of mean c of g velocity values does not indicate any specific trend as stepping rate alters (Figures 19 and 20).

Tension-time integrals in relation to physiological effort : fixed-time integrals

Starr (1951) suggested that the tension-time integral could be used as a measure of physiological effort in a gross work task. This view is not supported by the present data.

In a complete cycle in which starting and finishing velocities are equal, the tension-time integral, $\int_{t_1}^{t_2} T \cdot dt$, can be shown equal to $m \cdot g \cdot (t_2 - t_1)$.

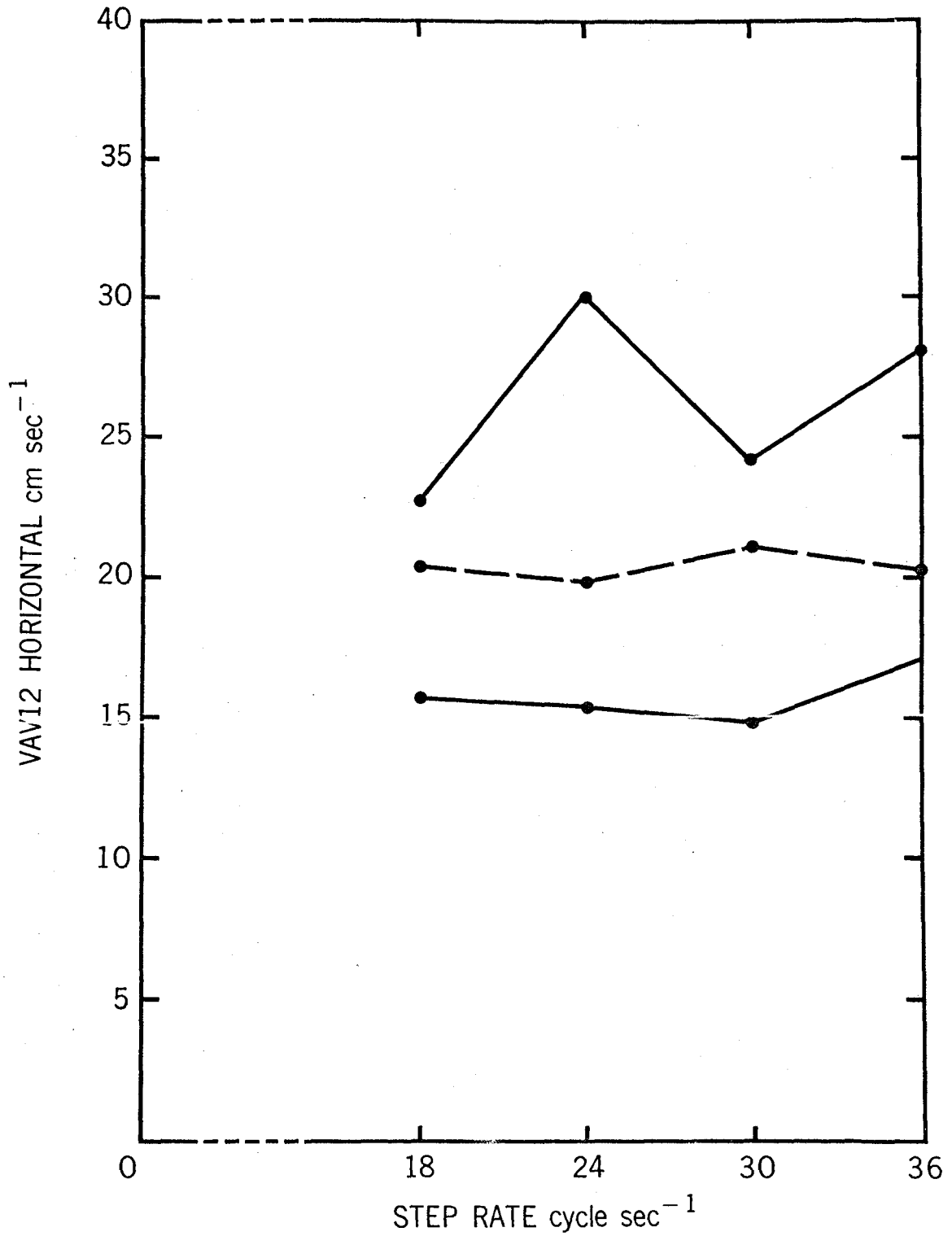


FIG. 19. Showing the range (solid lines) and median (broken line) of 8 values of the average horizontal velocity of the whole-body C of G during step phase 1-2, for 4 subjects at 4 step rates.

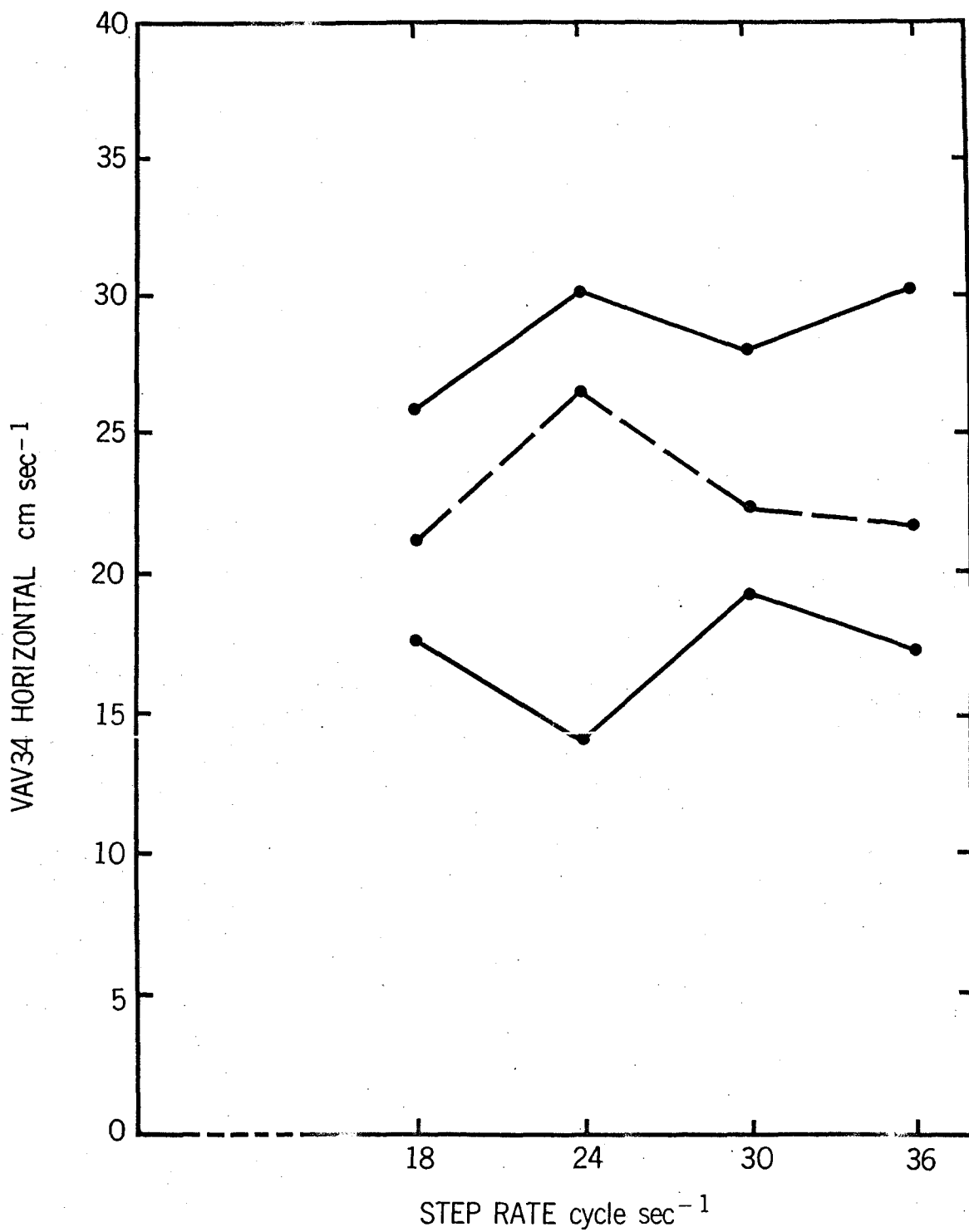


FIG. 20. Showing the range (solid lines) and median (broken line) of 8 values of the average horizontal velocity of the whole-body C of G during step phase 3-4, for 4 subjects at 4 step rates.

From Equation 10

$$\begin{aligned}
 \int_{t_1}^{t_2} T \cdot dt &= m \int_{t_1}^{t_2} (a-g) \cdot dt \\
 &= m \int_{t_1}^{t_2} a \cdot dt - m \int_{t_1}^{t_2} g \cdot dt \\
 &= m \int_{t_1}^{t_2} \frac{dv}{dt} \cdot dt - m \int_{t_1}^{t_2} g \cdot dt \\
 &= m \int_{t_1}^{t_2} dv - m \int_{t_1}^{t_2} g \cdot dt
 \end{aligned}$$

Since $v = f(t)$ and $dv = f'(t) \cdot dt$

$$\begin{aligned}
 \int_{t_1}^{t_2} T \cdot dt &= m \int_{t_1}^{t_2} f'(t) \cdot dt - m \cdot g \cdot (t_2 - t_1) \\
 &= m [f(t)]_{t_1}^{t_2} - m \cdot g \cdot (t_2 - t_1) \\
 &= m (v_2 - v_1) - m \cdot g \cdot (t_2 - t_1)
 \end{aligned}$$

$$\int_{t_1}^{t_2} T \cdot dt = -m \cdot g \cdot (t_2 - t_1) \quad \text{if } v_2 = v_1 \quad \dots (11)$$

Since g is negative in the sign convention used, the integral will have a positive value. The tension-time integral, therefore, is directly proportional to the time period over which the integral extends.

It follows therefore that the tension-time integral for a fixed time of stepping at any rate would be the same. For example, for one minute of stepping, the integral would equal 60 m.g. dyne sec whatever the stepping rate, but the metabolic cost (physiological effort) per unit time varies very appreciably (Figure 21). Thus Starr's contention seems not to be sustained.

It may be noted that the movement time period considered in Starr's study was 2 seconds, and he reported the tension-time integral for slower movement to be 1934.5×10^6 dyne sec. As explained above, from purely theoretical considerations

$$\int_{t_1}^{t_2} T \cdot dt = -m \cdot g \cdot (t_2 - t_1)$$

Since, in Starr's study, $m = 1$ Kg, $g = -981$ cm sec⁻², and $(t_2 - t_1) = 2$ sec, then

$$\begin{aligned} \int_{t_1}^{t_2} T \cdot dt &= 1000 \cdot 981 \cdot 2 \text{ dyne sec} \\ &= 1962 \times 10^3 \text{ dyne sec} \end{aligned}$$

Starr's value (1934.5×10^6 dyne sec) seems mis-reported, being too

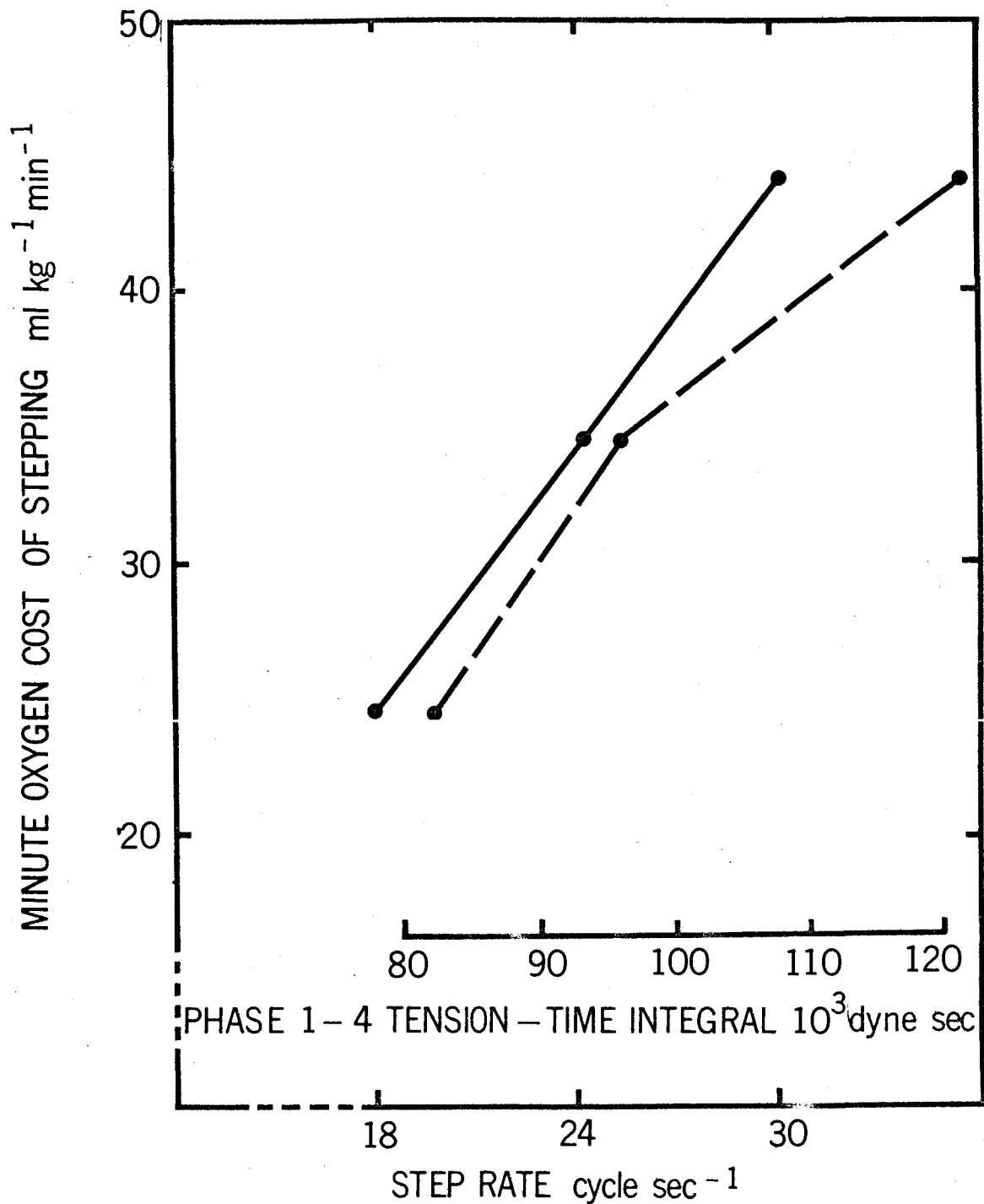


FIG. 21. Showing change in minute oxygen cost of stepping per kg of body weight in response to increased stepping rate (solid line); and the relationship between minute oxygen cost of stepping and the phase 1-4 tension-time integral (broken line).

great by a factor of 10^3 .

Starr was led to hypothesising a simple correlation between the tension-time integral and physiological effort by the fact that he obtained an integral of value 2996.8×10^6 dyne sec: seemingly should be $\times 10^3$ for the faster action. The conclusion is spurious however, for it was only because a downward acceleration greater than g was recorded. For all cases when the maximum downward acceleration is less than g , the tension-time integrals must have the same value, m.g. $(t_2 - t_1)$, which is independent of velocities and accelerations reached.

In the case of bench stepping, no downward accelerations greater than g were recorded: however, to explain the Starr finding more thoroughly, the general theory of how the tension-time integral, summated over a fixed time period, becomes dependent on the velocities and accelerations reached in those cases when downward accelerations in excess of g are observed, is given in Appendix 7.

Tension-time integrals in relation to physiological effort : action-phase integrals

A second method of considering tension-time integrals is to consider integral values for one fixed phase of action rather than during a fixed time period ("action-phase" tension-time integrals).

This was done in the present study: the phases of action considered were those of phases 1-2, 2-3, 3-4, and 1-4 (Figure 12, page 41). The average tension-time integrals for phase 1-4 (T114), for stepping rates of 36, 30, 24, and 18 cycles per minute, were respectively 73.7, 82.3, 95.8, and 122.0, all $\times 10^3$ dyne sec. These values are, as shown in Equation 11,

directly linearly dependent on the respective average phase 1-4 durations (Figure 22). Thus a tension-time integral obtained for any chosen phase is simply a fixed multiple of the duration of the phase - equal, in fact, to m.g times the phase duration.

Figure 21 shows the non-linear relationship between metabolic cost and the phase 1-4 tension-time integral. On the same graph is shown the linear relationship between metabolic cost and stepping rate.

The deviation of the first curve from linearity occurs because the phase 1-4 tension-time integral does not vary linearly with stepping rate; instead, because of the direct relationship between the tension-time integral and the phase duration (Equation 11), they co-vary in the same non-linear manner as does the phase 1-4 duration with stepping rate (Figure 23).

If phase 1-4 duration decreased in a proportionate manner as stepping rate increased, it would do so in accordance with the rectangular-hyperbolic relationship:-

$$\text{Phase 1-4 duration} \times \text{Stepping Rate} = \frac{60}{Y} \quad \dots (12)$$

where,

$$\frac{1}{Y} = \left[\frac{\text{Phase 1-4 duration}}{\text{Total cycle duration (0-0')}} \right] \quad 18 \text{ cycles/min}$$

This would be almost linear over the range of stepping rates examined (Figure 23). As stepping rate increases above 24 cycles per minute, the

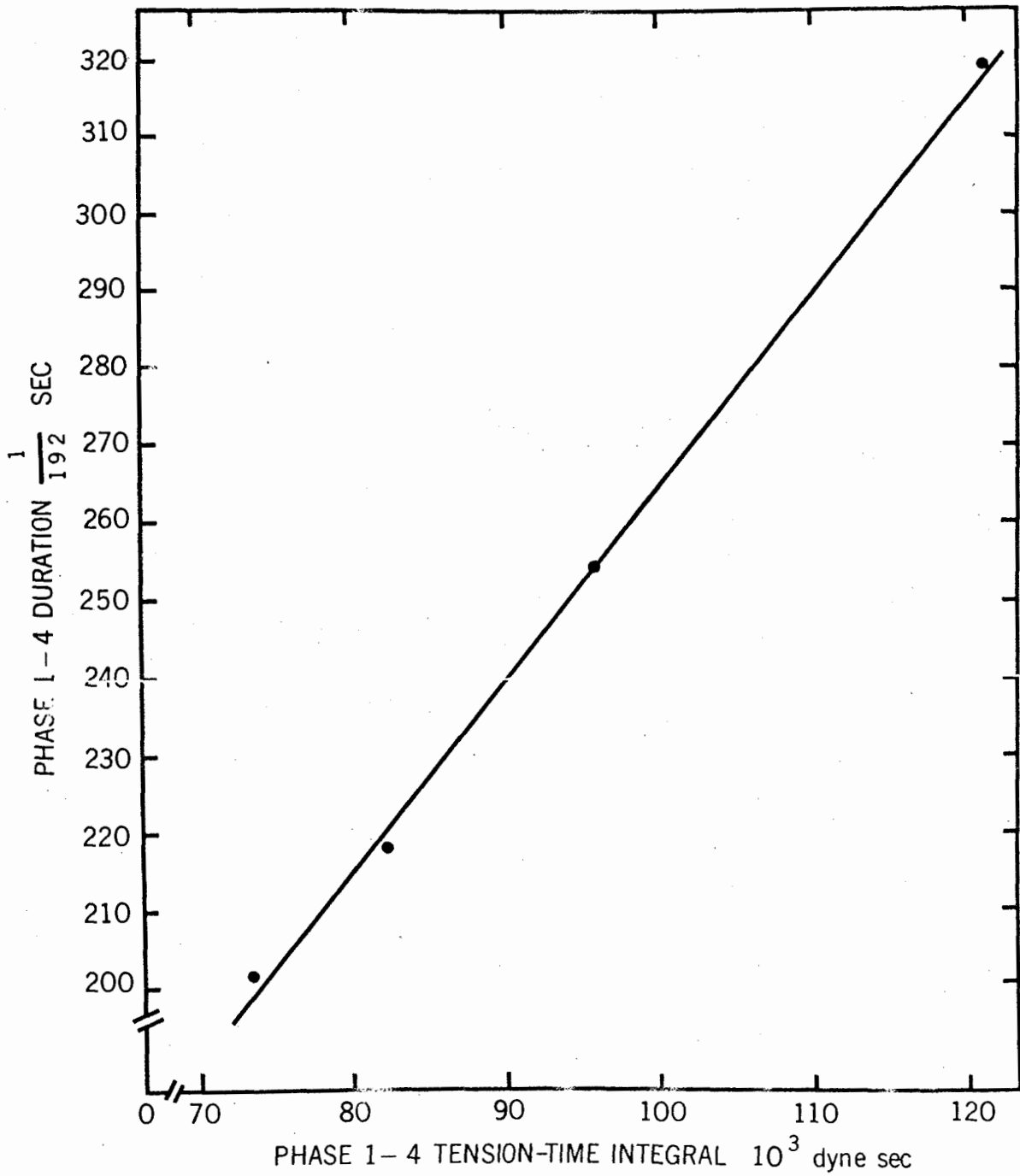


FIG. 22. Showing the linear relationship between the phase 1-4 duration and the phase 1-4 tension-time integrál. Units of phase 1-4 duration are $\frac{1}{8 \times 24}$ sec.

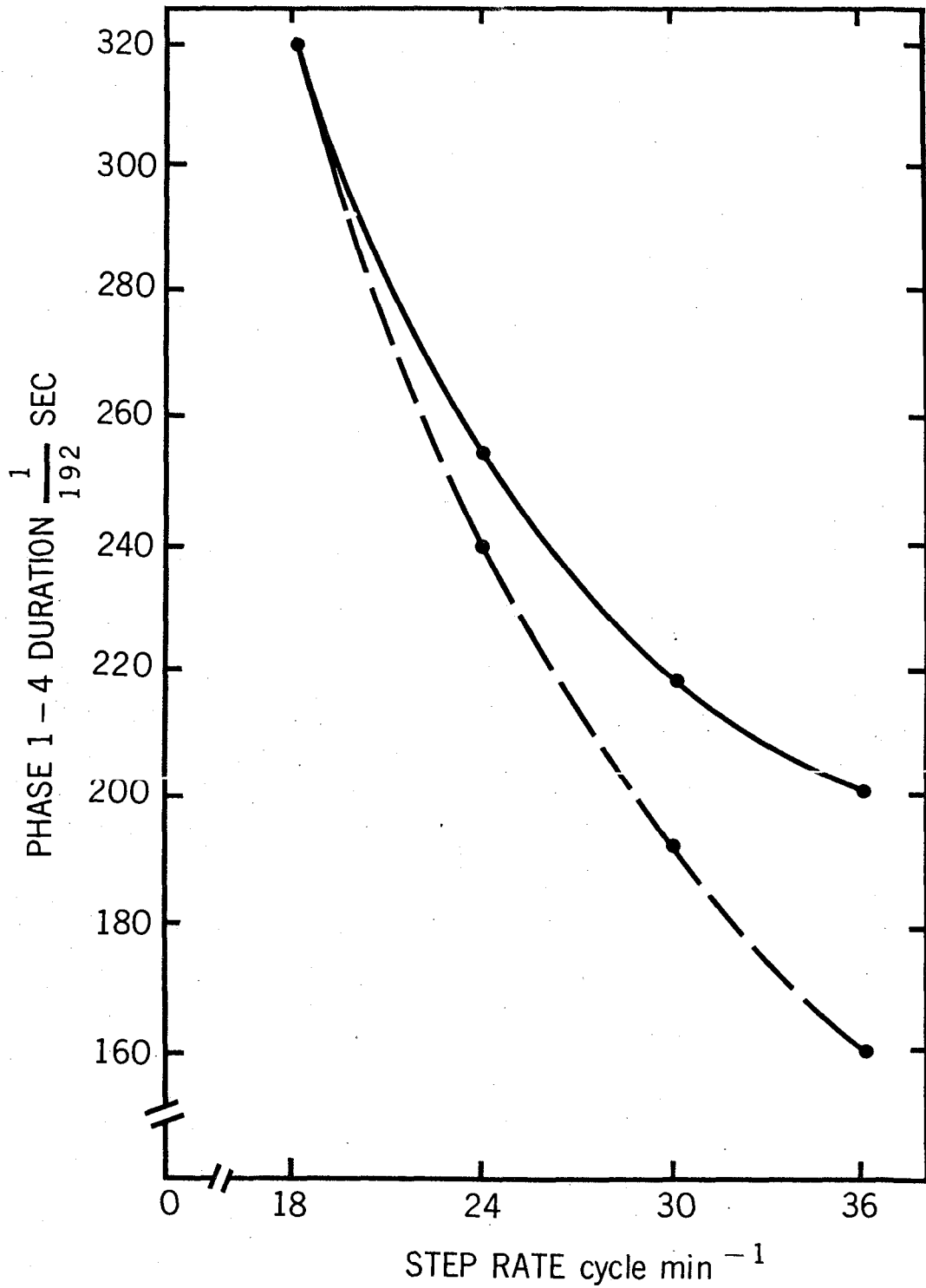


FIG. 23. Showing the observed change in phase 1-4 duration in response to increased stepping rate (solid line) and the expected change assuming that the phase duration decreases in a proportionate manner as step rate increases (broken line). Units of phase 1-4 duration are $\frac{1}{8 \times 24}$ sec.

phase 1-4 duration does not decrease in a proportionate manner: instead, it decreases only slightly (Table XI, Figure 23). This is the cause of the discontinuity in the $\dot{V}O_2$ vs. phase 1-4 duration curve (Figure 21).

Relation of acceleration-time and acceleration-distance integrals

The relationship was investigated by considering the ratio $\int a'.ds$: $\int a'.dt$ (denoted R) for the phases of the cycle :-

- 1) 1-2 the 'up phase' of the whole body (R12)
- 2) 3-4 the 'down phase' of the whole body (R34)

It was subsequently realised that these ratios would yield the average velocity of movement during the phases considered. Consider any phase of duration (t_2-t_1) in which the initial and final velocities are equal, and during which the body rises (s_2-s_1) units. Then,

$$R = \frac{s_2 \int a'.ds}{s_1 \int_{t_1}^{t_2} a'.dt}$$

$$= \frac{s_2 \int (a-g).ds}{s_1 \int_{t_1}^{t_2} (a-g).dt}$$

$$= \frac{\frac{s_2}{s_1} \int a.ds - \frac{s_2}{s_1} \int g.ds}{\frac{t_2}{t_1} \int a.dt - \frac{t_2}{t_1} \int g.dt}$$

but both $\frac{s_2}{s_1} \int a.ds$ and $\frac{t_2}{t_1} \int a.dt$ are equal to zero when the velocities at t_1 and t_2 are equal (page 66)

$$\begin{aligned} \text{Therefore, } R &= \frac{-\frac{s_2}{s_1} \int g.ds}{-\frac{t_2}{t_1} \int g.dt} \\ &= \frac{g (s_2 - s_1)}{g (t_2 - t_1)} \\ &= \text{VAV} \qquad \dots (13) \end{aligned}$$

(the average velocity of movement
in the period considered)

The close correspondence of the observed values of R (Table IX, page 53), and VAV (Table VII, page 51) for both horizontal and vertical movement during the phases considered, confirms the theoretical conclusions. The integral ratio R, therefore is not related to Hill's characteristic equation constant, b.

Tension-time integrals in relation to physiological effort : work-phase integrals

It was demonstrated earlier that physiological effort could not be simply related to fixed tension-time integrals of muscular action. The idea was considered that difficulties in this approach might be circumvented by examining the apportionment to positive, negative and static muscular action of all muscular effort in a complete action cycle. This requires separate consideration of the tension-time integrals of different muscular work phases (concentric, eccentric and isometric).

Hypothesising that the metabolic energy consumption of muscle, ϕ , is related to the tension-time integral during time t sec, then:

$$\phi_t = b \int_a^t T \cdot dt \quad \dots (14)$$

where \int_a^t denotes that the duration between upper and lower integral limits equals t seconds.

Therefore
$$b = \frac{\phi_t}{m \int_a^t a' \cdot dt} \quad \dots (15)$$

In extension of Equation 8, equating the metabolic energy cost with the free energy made available, then the overall efficiency of muscular work is defined as,

$$\text{Efficiency} = \frac{\text{Mechanical Work Done}}{\text{Metabolic Energy Cost}}$$

$$\text{Therefore Efficiency} = \frac{m^t \int a'.ds}{\Phi_t} \dots (16)$$

Then Equation 15 may be expressed as:

$$b = \frac{m^t \int a'.ds}{m^t \int a'.dt} \times \frac{1}{\text{Efficiency}} \dots (17)$$

To take account of the apportionment of concentric, static and isometric action phases, suppose that during one step cycle, occupying time t_c , periods of concentric, static and eccentric action of respective duration $t_{p/c}$, $t_{s/c}$, and $t_{n/c}$ occur. Then in extension of Equation 14,

$$\Phi_{p/c} = b_p \cdot \int_{t_{p/c}} T \cdot dt \dots (18)$$

$$\Phi_{s/c} = b_s \cdot \int_{t_{s/c}} T \cdot dt \dots (19)$$

$$\Phi_{n/c} = b_n \cdot \int_{t_{n/c}} T \cdot dt \dots (20)$$

The total metabolic cost per cycle, $\Phi_{tot/c}$ is then

$$\Phi_{tot/c} = b_p \cdot \int_{t_{p/c}} T \cdot dt + b_s \cdot \int_{t_{s/c}} T \cdot dt + b_n \cdot \int_{t_{n/c}} T \cdot dt \dots (21)$$

However, for any phase in which initial and final velocities are equal then $\int T \cdot dt$ is identical with $m \cdot g \cdot t$. Then equations 18, 19 and 20 become

$$\Phi_{p/c} = b_p \cdot m \cdot g \cdot t_{p/c} \quad \dots (22)$$

$$\Phi_{s/c} = b_n \cdot m \cdot g \cdot t_{s/c} \quad \dots (23)$$

$$\Phi_{n/c} = b_n \cdot m \cdot g \cdot t_{n/c} \quad \dots (24)$$

and Equation 21 becomes

$$\Phi_{tot/c} = b_p \cdot t_{p/c} + b_s \cdot t_{s/c} + b_n \cdot t_{n/c} \quad \dots (25)$$

For a stepping rate of n cycles per min

$$\frac{\dot{\Phi}_{tot}}{m \cdot g} = b_p \cdot \dot{t}_p + b_s \cdot \dot{t}_s + b_n \cdot \dot{t}_n \quad \dots (26)$$

where \dot{t}_p , \dot{t}_s and \dot{t}_n are respectively the durations spent per minute in concentric, static, and eccentric action.

Further consideration of Equation 14 led to its rejection as a fundamental relationship in the correlation of physiological and mechanical parameters of muscular performance.

If we consider, in the simplest case, a muscular work task requiring application of constant force, T , for a fixed time - for example ergometer cycling - then the tension-time integral for a work duration t_p would be $T \cdot t_p$. On the basis of the model proposed, this would be associated with a metabolic energy consumption ϕ_{t_p} . However, if the cycling rate is doubled against the same force, T , the tension-time integral for a fixed time, t_p , would still be $T \cdot t_p$, but the external mechanical work done is doubled, since it is a direct linear function of pedalling rate. Since the metabolic cost, ϕ_{t_p} , is dependent on the mechanical work done, it also would increase. The fixed-time tension-time integral and the metabolic energy consumption cannot therefore be related, and the model is proved false. Action-phase integrals (over one pedalling cycle) are inversely (hyperbolically) related to pedalling rate (c.f. page 70) and related to metabolic cost in a non-causative way.

In bench stepping, although instantaneous force and velocity are not independent as in the simple case of constant-velocity ergometer cycling, a parallel argument holds. In a positive work phase occupying time $t_{p/c}$, in which initial and final velocities are equal the model predicts that Equation 22 would hold - that is, the metabolic cost of the phase would be dependent only on its duration. Further it would follow that a metabolic energy cost $\phi_{p/c}$ would be associated with that phase regardless of the external work done in it. One consequence of this would be that the minute metabolic cost of stepping onto benches of different heights (at the same step rate) would be the same, and this

has been shown not to be the case. (Passmore and Durnin, 1950).

The empirical data of this study corroborate the theoretical reasoning: although the average minute oxygen costs of stepping at 30, 24 and 18 cycles per minute were respectively 44.0, 34.5 and 24.6 ml/min Kg (Table V), the average durations spent per minute in concentric action (t_p) hardly varied, being 27.0 seconds 25.4 seconds, and 23.7 seconds respectively. Durations spent per minute in isometric action were respectively 5.9, 9.3 and 12.7 seconds. Since concentric muscular action has a much greater metabolic energy cost than static action, large changes in the overall energy cost of stepping are unlikely to have been caused by such minimal increases in t_p or by the larger increases in t_s .

Figure 21 shows the linear relationship between metabolic energy consumption (ml oxygen per kg of body weight) and stepping rate. It follows that the metabolic energy cost bears a linear relationship to the gravitational work done: Lukin and Ralston (1968) found the same relationship in consideration of level and grade walking, but this was not so for sprint running (Fenn, 1930).

Relationship of gross parameters to thermodynamic parameters at cellular level and definitions of efficiency

The immediate energy for muscular contraction is furnished by hydrolysis of adenosine triphosphate (ATP). ATP is restored, ultimately, by oxidation of foodstuffs, and, in a steady state, the rate of utilisation of ATP is related to oxygen consumption (Whipp and Wasserman,

1969). For each mole of oxygen consumed 6 moles of ATP are utilised.

It has been shown that under conditions of temperature and intracellular pH approximating those of the body, the free energy change, ΔG , associated with ATP hydrolysis is approximately - 11,000 cal per mole (Krebs and Kornberg, 1957; Wilkie and Woledge, 1967).

The contraction-coupling efficiency is equal to the ratio of the external mechanical work done to the corresponding free energy of hydrolysis of ATP. Hence, if \dot{O} equals the oxygen cost per minute of steady-state activity (litres per minute), and \dot{W} is the external work rate in kilocalories per minute, then, using the values quoted above, the contraction-coupling efficiency, E_{cc} , is

$$E_{cc} = \frac{\dot{W}}{2.95 \times \dot{O}} \times 100\% \quad \dots (27)$$

Davies (1963; 1965) found this efficiency to be in the range 35% - 50% for isolated muscles, the value varying for different muscles. Whipp and Wasserman (1969) found a value of 49% for ergometer cycling when using the oxygen consumed in excess of that used in unloaded bicycle pedalling as the oxygen cost of the work task.

From the mean external work rate (calculated from Table X) and the average minute oxygen cost of stepping (Table V), the average contraction-coupling efficiency of muscular work for each subject at each stepping rate was calculated using Equation 27 (Table XII).

TABLE XII. Showing contraction-coupling efficiency in bench stepping (a) using exercise and recovery oxygen consumption to calculate oxygen cost and unloaded pedalling as baseline (b) using steady-state $\dot{V}O_2$ to calculate oxygen cost and unloaded pedalling as baseline (c) using steady-state $\dot{V}O_2$ to calculate oxygen cost and rest as baseline.

Subject	Step Rate Cycle ⁻¹ min ⁻¹	E _{cc} %		
		(a)	(b)	(c)
MM	30	45.1	45.8	42.3
GS	30	49.8	49.2	43.8
HK	30	45.2	46.1	41.5
RT	30	48.2	50.2	46.5
MM	24	52.9	52.6	47.6
GS	24	49.9	53.6	47.8
HK	24	49.2	48.1	43.0
RT	24	51.6	51.1	46.3
MM	18	57.2	59.3	49.8
GS	18	47.3	51.6	43.7
HK	18	51.3	50.1	45.1
RT	18	64.0	61.7	55.7

Using steady oxygen consumption to calculate minute oxygen cost of stepping (Method 2, page 47), and using rest as baseline, mean values of E_{cc} were 48.6% and 46.2% at stepping rate 18 and 24 cycles per minute respectively. These are very close to Whipp and Wasserman's reported value of 49%. It is noted however that the calculated values in the present study represent an average efficiency of alternating positive and negative work, the respective positive and negative work rates both being 563.5 kgm per minute - considerably in excess of the rate used by Whipp and Wasserman (340 kgm per minute).

Using unloaded cycling as baseline, calculated contraction-coupling efficiencies were somewhat higher (respectively 55.7% and 51.4% using steady oxygen consumption to calculate minute oxygen cost of stepping; and 55.0% and 50.9% using exercise and recovery oxygen consumption to assess minute oxygen cost of stepping).

Krebs and Kornberg (1957) and Lehninger (1965) suggest the efficiency of phosphorylative coupling, E_{pc} , to be about 60% and therefore the overall efficiency of muscular work, E_{tot} , is

$$E_{tot} = \frac{E_{pc} \times E_{cc}}{100} \% \quad \dots (28)$$

Using average contraction-coupling efficiencies of 48.6% and 46.2% for stepping rates of 18 and 24 cycles per minute, average total efficiencies are therefore 29.2% and 27.7% at the two stepping rates. Values at higher stepping rates were not calculated since at such high work rates the

physiological response may no longer be a steady-state one.

CHAPTER VI

SUMMARY

Chapter I considered that complication arises in the analysis of the energetics of muscular contraction because of the impossibility of assessing dynamic and static muscular action in similar mechanical terms.

Since the metabolic effort associated with isometric muscular action has been shown to be correlated with the impulse applied externally (that is the product of the externally-applied force and its time of application), the idea has been examined that impulse measures might be useful correlates of metabolic effort in dynamic work tasks.

The tension-time integral, $\int_{\text{lims}} T \cdot dt$, defined as the definite time integral of an externally-applied, variable force, T , between chosen time limits, has been examined as a possible correlate of physiological effort in the dynamic gross muscular work task of bench-stepping. Stepping rate was varied to provide work tasks of different intensity, and physiological effort was measured in terms of the metabolic energy cost, estimated from respiratory gas exchange measurements.

Tension-time integrals were considered in three ways:

- (1) "fixed-time" tension-time integrals, in which the same integral time limits were used for all work tasks.
- (2) "action-phase" tension-time integrals, in which the integral time limits were those of particular movement phases whose duration varied from one work task to another.

- (3) "work-phase" tension-time integrals, in which the integral time limits were those of a particular type of muscular action - namely either concentric, isometric or eccentric action.

It was found that none of these interpretations of the tension-time integral suggested a useful mechanical parameter for comprehensive assessment of physiological effort.

The first method, because of a proved linear relationship between the definite tension-time integral and duration of the phase considered, yielded integrals entirely independent of the metabolic cost of the work task. A particular case of dependence previously reported (Starr, 1951), suggesting general validity of this dependence, was explained and shown to be a spurious conclusion arising from special features of the work tasks used.

Action-phase tension-time integrals, because of the relationship between the integrals and the period durations, were shown to be simple multiples of the phase durations. These latter were found to vary in a complex manner as step rate altered, and because metabolic energy cost varied linearly with step rate, the relationship of action-phase tension-time integrals to metabolic energy cost was complicated, and shown not to be useful.

The third method of consideration (work-phase integrals) lacked correlative validity because of the independence of the tension-time integral during a chosen work phase and the external mechanical work performed in that phase.

In summary, it is concluded that the tension-time integrals of dynamic muscular work, however considered, cannot be related to the metabolic cost of the work.

Metabolic energy cost was shown to be linearly related to stepping rate, and so to the external mechanical work done. It was also estimated that the contraction-coupling efficiency of the muscular work performed was approximately 49% at low work rates.

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APPENDIX 1

Respiratory gas collection data sheet.

OXYGEN UPTAKE DATA SHEET

97

NAME

DATE

STEP RATE

ANALYSIS

WEIGHT

NOTES

A	C	D	E	F	G	H
Bar. Press. mm Hg	Calib. .O ₂ Readg. Divs	% O ₂ in Calib. Gas	Calib.CO ₂ Readg. Divs	% CO ₂ in Calib. Gas	% O ₂ in Inspired Air	% CO ₂ in Inspired Air

Time	Temp C	Volumeter Reading (Litres)
0		
1		
2		
3		
4		
5		
99		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		

O ₂ Analyser Readg(Divs)	CO ₂ Analyser Readg(Divs)	..Min
		1
		2
		3
		4
		5
		6
—	—	
		7
		8
		9
		10
		11
		12
		13
		14
		15
—	—	

APPENDIX 2

Computer program for general polynomial
least-squares curve-fitting.

APPENDIX 3

Computer program for calculation of oxygen uptake throughout exercise.

```

C
C OXYGEN UPTAKE DETERMINATION
C VO2 USED IS CALCULATED IN LITRES FOR EACH SEPARATE MINUTE
C
C THIS PROGRAMME WAS DESIGNED BY HARRY A. KING AND OTTO F. MATT
C
C MULTIPLE DATA SETS ALLOWED
C INTEGER TITLE(20)
C REAL MTEMP(16),VU(16),O2R(16),CO2R(16),TABLE(100),N2PC
C READ(5,27)TABLE
C PARTIAL PRESSURES OF H2O (FROM CARPENTER'S TABLES)
10 READ(5,21,END=15)TITLE
21 FORMAT(20A4)
WRITE(6,22)
22 FORMAT('1',38X,'O X Y G E N U P T A K E D E T E R M I N A T I O
IN')
WRITE(6,23)TITLE
23 FORMAT('-',25X,20A4)
READ(5,24)A,C,D,G,H
C A IS BAROM.PRESSURE,B IS SCALE DEFLECTION(DIVS) CORRESPONDING TO D % O2
C G IS % O2 IN INSPIRED AIR,H IS % CO2 IN INSPIRED AIR
24 FORMAT(5F10.3)
WRITE(6,25)
25 FORMAT('-',6X'MINUTE * V'' AIR ATPS * MEAN TEMP * V'' AIR STP
1D * % O2',5X,'*' % CO2 * % N2',5X,'*',2X,'RER',2X,'*',2
2X,'VO2 USED **')
26 FORMAT(12,8X,4F10.3)
27 FORMAT(20F4.2)
C
C ASSIGN 13 TO JUMP
DO 13 J=1,16
14 READ(5,26)I,MTEMP(J),VU(J),O2R(J),CO2R(J)
C RESPECTIVELY,READING NO.,TEMPERATURE,VOLUMETER READING,
C O2 DEFLECTION,CO2 DEFLECTION
IF(I.NE.99)GO TO 11
VU(J-1)=VU(J)
GO TO 14
11 GO TO JUMP,(12,13)
C
12 VU(J-1)=VU(J)-VU(J-1)
MTEMP(J-1)=(MTEMP(J)+MTEMP(J-1))/2.
13 ASSIGN 12 TO JUMP
C
DO 16 J=1,15
K=(MTEMP(J)-19.9)*100.
IF((K/10)*10.NE.K)GO TO 17
B=TABLE(K/10)
GO TO 18
17 B=(TABLE(K/10)+TABLE((K/10)+1))/2.
C INTERPOLATION OF PART.PRESS.OF H2O AT NON-TABULATED TEMPERATURE
18 VC=((A-B)*273.*VU(J))/(760.*(273+MTEMP(J)))
O2PC=O2R(J)*D/C
CO2PC=0.000336*CO2R(J)*CO2R(J)+0.03379*CO2R(J)+0.264
C INDEPENDENTLY-DEDUCED CO2 CONVERSION EQUATION
N2PC=100.-O2PC-CO2PC
VO2=VC/100.*(G*N2PC/(100.-G-H)-O2PC)
RQ=VC/100.*(CO2PC-N2PC*H/(100.-G-H))/VO2
16 WRITE(6,28)J,VU(J),MTEMP(J),VC,O2PC,CO2PC,N2PC,RQ,VO2
28 FORMAT(9X,12,6X,'*',6(F10.3,3X,'*'),F5.1,2X,'*',F10.3,3X,'*')
GO TO 10
50 FORMAT('1','THIS IS A DUMMY LAST PAGE')
15 WRITE(6,50)
STOP
END

```


APPENDIX 4

Data sheet for Vanguard Motion Analyser.

FILM ANALYSIS: VANGUARD READINGS

FRAME NO.

	RIGHT		LEFT	
	V	H	V	H
HIP			0.00	0.00
KNEE				
ANKLE				
FOOT				
SPOT			0.00	0.00

FRAME NO.

	RIGHT		LEFT	
	V	H	V	H
HIP			0.00	0.00
KNEE				
ANKLE				
FOOT				
SPOT			0.00	0.00

FRAME NO.

	RIGHT		LEFT	
	V	H	V	H
HIP			0.00	0.00
KNEE				
ANKLE				
FOOT				
SPOT			0.00	0.00

FRAME NO.

	RIGHT		LEFT	
	V	H	V	H
HIP			0.00	0.00
KNEE				
ANKLE				
FOOT				
SPOT			0.00	0.00

FRAME NO.

	RIGHT		LEFT	
	V	H	V	H
HIP			0.00	0.00
KNEE				
ANKLE				
FOOT				
SPOT			0.00	0.00

FRAME NO.

	RIGHT		LEFT	
	V	H	V	H
HIP			0.00	0.00
KNEE				
ANKLE				
FOOT				
SPOT			0.00	0.00

APPENDIX 5

Computer program for calculation and graphical
display of centre of gravity movements.

```

INTEGER FRAME
REAL A(1,3),R(6),X(20),Y(20),Z(20),CGV(20),CGH(20),DFRAME(20),
1 IBUF(1024),TITLE(20)
CALL PLOTS(1,RUF,1024)
997 READ(5,2010,FN)=998) TITLE
2010 FORMAT(20A4)
WRITE(6,205) TITLE
DO 5 I=1,200
5 DFRAME(I)=1-1
READ(5,100,FNO=998) NOBS,NCNTRL
READ(5,105)Y1,Y2,Y3,Y4,Y5
READ(5,205)S2LJN,HORLOW
2050 FOPMAT(2F10,4)
ADJ=S2LJN-HORLOW
IF(NCNTRL.EQ.0) GO TO 10
READ(5,101)X(1),Y(1),Z(1),I=1,NDRS)
DO 20 I=1,3
R(I)=0.
DO 20 J=1,3
20 A(I,J)=0.
DO 40 I=1,NDRS
A(1,1)=A(1,1)+X(I)
A(2,1)=A(2,1)+X(I)*X(I)
A(3,1)=A(3,1)+X(I)*Y(I)
A(1,2)=A(1,2)+Y(I)
YSO=Y(1)+Y(I)
A(1,3)=A(1,3)+YSO
A(2,3)=A(2,3)+YSO*Y(I)
A(3,3)=A(3,3)+YSO*YSO
R(1)=R(1)+Z(I)
R(2)=R(2)+Y(I)*Z(I)
R(3)=R(3)+YSO*Z(I)
40 C BETAG AND ALPHA=H.
BETA=(A(1,2)+Y(1)+Y(1))/(A(1,1)+Y-X(1))
ALPHA=Y(1)-BETA*(X(1))
A(1,1)=NOBS
A(2,1)=A(1,2)
A(2,2)=A(1,3)
A(3,1)=A(1,3)
A(3,2)=A(2,3)
CALL GAUSS(A,R,3,1,3,DET)
WRITE(6,210) DET
210) FORMAT(' VALUE OF DETERMINANT IS',F15.7)
IF(ABS(DET).LT.1.E-4) GO TO 999
DELTA=R(1)+R(2)+Y(1)+R(3)+Y(1)+Y(1)
WRITE(6,2003) DELTA
2003) FORMAT(' ODDIRECTION CN CONSTANT IS ',F10.4)
R(1)=R(1)-DELTA
R(6)=R(3)*BETA*BETA
R(5)=BETA*2.*R(3)*ALPHA+R(2)
R(4)=R(1)+ALPHA*R(2)+ALPHA*ALPHA*R(3)
WRITE(6,2000)BETA,ALPHA
2000) FORMAT('SCALE1=',F8.2,'*SC2=',F9.2)
WRITE(6,2001)R(3),R(2),R(1)
2001) FOPMAT('OREAL=',F9.3,'*SC1=',F9.3,'*SC2=',F9.3)
WRITE(6,2002)R(6),R(5),R(4)
2002) FOPMAT('OREAL=',F9.3,'*SC2*SC2=',F9.3,'*SC2+',F9.3)
WRITE(6,1120) R
1120) FOPMAT('0',6F16.5//)
WRITE(7,120) R
50 TO 50
10 READ(5,120) R
50 CONTINUE
JJ=1
DO 55 J=1,200
READ(5,130) FRAME,(X(I),I=1,20)
IF(FRAME.LT.0) GO TO 70
JJ=JJ+1
DO 60 I=1,20
IF(I/2.EQ.0) X(I)=X(I)+.08*ADJ
IF(I.EQ.0)OR.1.FO.20) X(I)=0.
IF(X(I).NE.0.)AND.1.NF.17) X(I)=2*(4)+R(5)+X(I)
U +R(4)*X(I)*Y(I)
IF(I.EQ.17) X(I)=R(1)+P(12)*X(I)+P(13)*X(I)*X(I)
60 CONTINUE
CGV(J)=(X(1)*Y(1)+X(5)+X(7))*Y2+(X(7)+X(11))*Y3+X(13)+Y(15))*Y4
+X(17)+Y5)/100.
CGH(J)=(X(2)*Y(1)+X(6)+X(8))*Y2+X(10)+X(12))*Y3+(X(14)+X(16))*Y4
+X(18)+Y5)/100.
55 WRITE(6,200) FRAME,X,CGV(J),CGH(J)
J=201
70 CONTINUE
J=JJ
J=J-1
AJ=J
XLNGTH=AJ/5.
DFRAME(J)=0.
DFRAME(J+2)=5.
J1=AJ/5+.3.
RESET=JJ1
CALL AXIS(0.,0.,'FRAME NUMBER',-12,XLNGTH,0.,0.,5.)
CALL SCALE(CGV,10.,J,1)
CALL AXIS(0.,0.,'VERTICAL CNTRF OF GRAVITY',26,10.,00.,
1 CGV(J+1),CGV(J+2))
CALL SYMBOL(0.2,9.6,.10,TITLE,0.,0)
CALL LINE(DFRAME,CGV,J,1,0,0)
CALL PLOT(RESET,0.,-3)
CALL AXIS(0.,0.,'FRAME NUMBER',-12,XLNGTH,0.,0.,5.)
CALL SCALE(CGH,10.,J,1)
CALL AXIS(0.,0.,'HORIZONTAL CNTRF OF GRAVITY',26,10.,00.,
1 CGH(J+1),CGH(J+2))
CALL SYMBOL(0.2,9.6,.10,TITLE,0.,0)
CALL LINE(DFRAME,CGH,J,1,0,0)
CALL PLOT(RESET,0.,-3)
GO TO 997
997 WRITE(6,210) DET
998 CALL PLOT(0.,0.,999)
STOP
100 FORMAT(7I5)
105 FORMAT(5F10,5)
110 FORMAT(6F10,5)
120 FORMAT(6E13,7)
130 FORMAT(15(1)F8,0)
200) FOPMAT(45X,'FRAME',14//54X,'RV',6X,'PH',6X,'LV',6X,'HM',45X,'HP',
1 2X,4(2X,F6.2)/45X,'KNEF',1X,4(2X,F6.2)/45X,'AKLF',
2 4(2X,F6.2)/45X,'FOOT',1X,4(2X,F6.2)/45X,'SPT',1X,
3 4(2X,F6.2)/45X,'CGV=',F10.5,4X,'CGH=',F10.5//)
205) FOPMAT(' ',7//45X,20A4//)
210) FOPMAT(' *** SYSTEM IS UNSOLVABLE. DET=',E14.8)
END

```

```

C      SUBROUTINE GAUSS (A,R,N,NR,ND, DET)
C      SUBROUTINE GAUSS   FFB. 68
C      GAUSSIAN ELIMINATION METHOD FOR THE SOLUTION OF N BY N MATRICES,
C      WHERE N IS EQUAL TO OR LESS THAN ND, BY TRANSFORMING INTO AN
C      UPPER TRIANGULAR FORM
C      NR = NUMBER OF RIGHT HAND SIDES TO BE SOLVED
C      A IS THE LEFT HAND MATRIX MADE UP OF THE COEFFICIENTS OF THE
C      UNKNOWNNS
C      R IS THE RIGHT HAND MATRIX
C      IN PLACE OF THE ZEROS IS THE PRODUCT FACTOR. PRODUCT FACTOR IS THE
C      NUMBER WHICH REDUCES ELEMENT
C      A(I,J) TO ZERO BY MULTIPLYING WITH THE DIAGONAL ELEMENT A(I,I) AND
C      SUBTRACTING THE RESULTANT
C      COMPUTED VALUES OF UNKNOWNNS ARE PLACED IN APPROPRIATE POSITIONS IN
C      R MATRIX. EG. X(3) IN ROW 3.
C      DET CONTAINS THE VALUE OF THE DETERMINANT OF THE A MATRIX.
C
C      REAL*8 P,Q,TOT
C      DIMENSION A(ND,1), R(ND,1)
C
C      FIND THE MAXIMUM, NON ZERO COLUMN VALUE
C      N1 = N-1
C      DO 2 J=1,N1
C      XMAX=A(J,J)
C      NN=J
C      JJ = J + 1
C      DO 3 I = JJ,N
C      IF (A(I,J) .LE. XMAX) GO TO 3
C      XMAX = A(I,J)
C      NN = I
3      CONTINUE
C      IF (ABS(XMAX) .GT. 1.0 E-20) GO TO 19
C      XMAX = 1.0 E-20
C
C      INTERCHANGE ROWS IF REQUIRED
19      IF (NN.EQ.J) GO TO 5
C      DO 6 K=1, N
C      TEMP = A(J,K)
C      A(J,K) = A(NN,K)
6      A(NN,K) = TEMP
C      ALSO FOR R
C      DO 14 K=1, NR
C      TEMP = R(J,K)
14      R(J,K) = R(NN,K)
C      R(NN,K) = TEMP
C
C      REDUCE TO UPPER TRIANGULAR FORM
C      P=1/A(J,J)
5      DO 2 L=JJ,N
C      Q = A(L,J)*P
9      A(L,J) = Q
C      DO 7 M =JJ,N
7      A(L,M) = A(L,M) - Q*A(J,M)
C      DO 8 MB = 1, NR
8      R(L ,MB) = R(L ,MB) - Q *R(J,MB)
2      CONTINUE
C
C      CALCULATION OF DETERMINENT
C      DET=1.
C      DO 778 I=1,N
778      DET=DET*A(I,1)
C      IF (DET .LT. 1.E-5) RETURN
C
C      CALCULATION OF SOLUTIONS
C
777      DO 11 K=1, NR
10      R(N,K) = R(N,K) / A(N,N)
C      DO 11 J=2,N
C      J1 = J-1
C      NJ = N-J1
C      JN=NJ + 1
C      TOT=0.0
C      DO 12 I=JN,N
12      TOT=TOT +A(NJ,I)* R(I,K)
11      R(NJ,K) = (R(NJ,K) - TOT ) / A(NJ,NJ)
C      RETURN
C      END

```

APPENDIX 6

Computer program to calculate and display graphically time derivatives of distance-time data; and to calculate acceleration-time and acceleration-distance integrals.

```

DIMENSION HEAD(19),V(200),Z(200),VY(200),VZ(200),AZ(200),
1 ARSAV(200),ARSAZ(200),AT(200),AVS(200),AZS(200),MP(8)
COMMON HEAD
DATA CAL/4,2E+10/
LOGICAL FLAG,FALSE,/
C
C READ IN PHYSICAL OF TIME INTERVAL
HEAD(S,1)0
1
1 FIRMAT(8,0)
M1,0/M
C
C READ IN HEADINGS AND NUMBER OF DATA POINTS (IN EACH ARRAY)
10 READ(S,20)N,HEAD
20 FIRMAT(15,1)N,AN
IF(N,1,0)GO TO 200
REAR(S,21)0
21 FIRMAT(8,0)
C
C READ IN VERTICAL(V) AND HORIZONTAL(Z) DATA
READ(S,30)IY(1),JY(1)N
READ(S,40)IZ(1),JZ(1)N
30 FIRMAT(15,2)IY,IZ
C
C COMPUTE VELOCITIES AND ACCELERATIONS
CALL DIRF(V,VS,VS1)
CALL DIRF(VZ,VZ1)
CALL DIRF(Z,VS,VS1)
CALL DIRF(Z,VZ,VZ1)
C
C COMPUTE ANSAV,ANSAZ (ADJUSTED ACCNS) AND AT = M(I-1),J=1,N
10 AT(1)=M(I-1,0)
ANSAV(1)=ANSAV(1)+M(I-1)
ANSAZ(1)=ANSAZ(1)+M(I-1)
M(I)=M(I-1)+1
C
C COMPUTE ARRAYS VYS AND VZS OF ABSOLUTE Y AND Z DISPLACEMENTS
VYS(1)=ANSAV(1)
VZS(1)=ANSAZ(1)
M(I)=M(I)+1
50 VYS(I)=VYS(I-1)+ANSAV(I)-V(I-1)
VZS(I)=VZS(I-1)+ANSAZ(I)-Z(I-1)
C
C READ IN CONTROL PARAMETERS FOR PLOTTING(NP) AND INTEGRATING
READ(S,55)INT1,INT2,INT3,INT4,NT2,NT3,NT4
55 F0RMA(11,4)S,F10,9
C
C IF NT2 = 0 NO INTEGRATING IS REQUIRED
IF(NT2,0,0)GO TO 56
C
C PERFORM REQUIRED INTEGRATIONS
CALL TRAPIN(INT1,INT2,AT,ANSAV,VY112)
CALL TRAPIN(INT2,INT3,AT,ANSAZ,VZ123)
CALL TRAPIN(INT3,INT4,AT,ANSAV,VY134)
CALL TRAPIN(INT1,INT2,ANSAZ,VZ123)
CALL TRAPIN(INT1,INT2,ANSAV,VY112)
CALL TRAPIN(INT2,INT3,ANSAV,VY123)
CALL TRAPIN(INT3,INT4,ANSAV,VY134)
CALL TRAPIN(INT4,N,ANSAV,VY14N)
CALL TRAPIN(INT1,INT2,AT,ANSAZ,VZ123)
CALL TRAPIN(INT2,INT3,AT,ANSAZ,VZ134)
CALL TRAPIN(INT1,INT2,ANSAZ,VZ123)
CALL TRAPIN(INT3,INT4,ANSAZ,VZ134)
CALL TRAPIN(INT4,N,ANSAZ,VZ14N)
M(I)=M(I)+1
M(I)=M(I)/CAL
VY12=VY112/YT112
VY34=VY134/YT134
VYAV=2.0*(VY12+VY34)/(VY12+VY34)
VZ23P1=VZ23P1
VZ23P2=VZ23P2
VZ12=VZ112/0.0
VZ34=VZ134/0.0
VYTOT=VY112*(VY101+VY14N)+VY12*VY34+VZ23P2
VZTOT=VZ112*(VZ101+VZ14N)+VZ12*VZ34+VZ23P2
ZK12=ZS112/ZT112
ZK34=ZS134/ZT134
ZKAV=2.0*(ZK12+ZK34)/(ZK12+ZK34)
DT12=(NT2-NT1)0.0
DT34=(NT4-NT3)0.0
VYAV12=(VYS(NT2)-VYS(NT1))/DT12
VYAV34=(VYS(NT4)-VYS(NT3))/DT34
ZVAV12=(AZS(NT2)-AZS(NT1))/DT12
ZVAV34=(AZS(NT4)-AZS(NT3))/DT34
VYAV=2.0*(VYAV12+VYAV34)/(VYAV12+VYAV34)
ZVAV=2.0*(ZVAV12+ZVAV34)/(ZVAV12+ZVAV34)
ZK23P1=VZ23P1
ZK23P2=VZ23P2
ZK12=ZS112/0.0
ZK34=ZS134/0.0
ZTOT=VZTOT*(ZS101+ZS14N)+ZK12*ZK34+ZK23P2
ZTOT=ZTOT*(ZS101+ZS14N)+ZK12*ZK34+ZK23P2
WRITE(6,150)HEAD
150 F0RMA(11,1)N,AN,A3
WRITE(6,151)M,T MASS = 1E+20,1 K(6,1)
151 F0RMA(11,1)N,AN
WRITE(6,160)
160 F0RMA(11,1)N,AN,CALCULATIONS,18X,17H VERTICAL RESULTS,2X,19H HORIZO
NITAL RESULTS/
WRITE(6,165)
165 F0RMA(2)H INTEGRALS OF ADJUSTED ACCN./2X,1ANSAV(ACCN,6) VS T,
1 5X,1ANSAZ(ACCN) VS T/41X,1UNITS ARE CM/SEC4
WRITE(6,170)VY112,ZT112,VY123,ZT123,VY134,ZT134,VY101,VY112,
170 VY112,VY123,ZS123,VY134,ZS134,VY14N,ZS14N
FIRMAT(11,2)H FROM T1 TO T2 = T112,3X,2E20,7/23H FROM T2 TO T
14 = T123,3X,2E20,7/23H FROM T3 TO T4 = T134,3X,2E20,7/10,31X,
1 1ANSAV(ACCN,6) VS S ANSAZ(ACCN) VS S/41X,1UNITS ARE (CM/SEC)2
170 11
170 F0RMA(11,2)H FROM S1 TO S2 = S112,3X,2E20,7/23H FROM S1 TO S2 = S112,3X,2E20,7/23
42E20,7/23H FROM S3 TO S4 = S123,3X,2E20,7/23H FROM S3 TO S4 = S134,3X,
42E20,7/23H FROM S4 TO S5 = S14N,3X,2E20,7/
WRITE(6,175)VY112,ZT112,VY123,ZT123,VY134,ZT134,VY14N,ZS14N
175 FIRMAT(11,2)H INTEGRALS OF INTEGRALS/21X,1UNITS ARE CM/SEC4/
1 180,21H S112/ZT112 = R12,4X,2E20,7/22H S134/ZT134
1 180,4X,2E20,7/22H AV OF R12,4X,2E20,7/22H

```

```

176 WRITE (6,176) VAV12,ZVAV12,VVAV34,ZVAV34,VVAV,ZVAV
FORMAT ('(10)MEAN VELOCITY CALCULATIONS',14X,'UNITS ARE (CM/SEC)')
1 TO (S2=S1)/(T2-T1) = VAV12,ZF20,7// (S3=S4)/(T4-T3) = VAV34,
2 ZF20,7// AV OF VAV12,VAV34 = VAV1,ZF20,7)
WRITE (6,180)YH12,ZH12,YH34,ZH34,YV23P1,ZV23P1,YV23P2,ZV23P2,YVHTOT
1,ZVHTOT,YVHTOT,ZVHTOT
180 FORMAT ('(10)MECHANICAL WORK EXPRESSIONS',14X,'UNITS ARE KCAL/T
1 140FROM S1 TO S2/13H (MASS*S112
1),HX,HH = W12,ZF20,7,ZF20,7/14H FROM S3 TO S4/13H (MASS*S134),HX,HH
2 = W34 ,E1H,ZF20,7/22H FROM S2 TO S3(DISS,11/13H (MASS*S123),HX
3,HH = W23P1,E1H,ZF20,7/22H FROM S2 TO S3(DISS,21/17H (MASS*1123*
4RAV),HX,HH = W23P2,E1H,ZF20,7// * TOTAL WORK (DISS,11// (MASS*
4TS1012,140)T// * (249444234P1) = *HTOT1,E1H,ZF20,7// (MASS*
4 * TOTAL WORK (DISS,21// 10H (MASS*(S101+S14
5N)/16H 441249344W23P2),SX,HH = *TOT2 ,E1H,ZF20,7)
56 DO 160 I=1,8
IF(INP(11,F0,0)GO TO 140
IF(FLAG) GO TO 59
PFLAG=.TRUE.
CALL PLOTS
CONTINUE
59 GO TO(60,70,80,90,100,110,120,130),I
60 CALL PLOTAL(X,Y,N,Z)VERTICAL DISPLACEMENT,21,4HTIME,4,H,0,1)
GO TO 140
70 CALL PLOTAL(X,Y,N,Z)VERTICAL VELOCITY,17,4HTIME,4,H,0,1)
GO TO 140
80 CALL PLOTAL(X,Y,N,Z)VERTICAL ACCELERATION,21,4HTIME,4,H,0,1)
GO TO 140
90 CALL PLOTAL(AVS,AHSAV,N,Z)HANS.VALUE(VERTICAL ACCN,+G),27,
130HANSOLUTE VERTICAL DISPLACEMENT,30,H,0,1)
GO TO 140
100 CALL PLOTAL(X,Z,N,Z)HORIZONTAL DISPLACEMENT,23,4HTIME,4,H,0,1)
GO TO 140
110 CALL PLOTAL(X,VZ,N,Z)HORIZONTAL VELOCITY,19,4HTIME,4,H,0,1)
GO TO 140
120 CALL PLOTAL(X,AZ,N,Z)HORIZONTAL ACCELERATION,23,4HTIME,4,H,0,1)
GO TO 140
130 CALL PLOTAL(AZS,AHSAZ,N,Z)HANS.VALUE HORIZONTAL ACCN,,26,
132HANSOLUTE HORIZONTAL DISPLACEMENT,32,H,0,1)
140 CONTINUE
GO TO 10
200 IF(FLAG) CALL PLOTAD
STOP
END
SUBROUTINE DIFF(Y,N,H)
C ROUTINE FOR 2ND-ORDER NUMERICAL DIFFERENTIATION ON N VALUES Y(J)
C SEPARATED BY AN EQUAL INTERVAL H
DIMENSION Y(N),0(N)
CWD,57H
NM1=N-1
D(1)=0.
DO 5 J=2,NM1
D(J) = C*(Y(J+1) - Y(J-1))
D(N) = C*(3.*Y(N) - 2.*Y(NM1) + Y(NM2))
RETURN
END
SUBROUTINE TRAPIN(MI,NF,XARRAY,AHSA,TRAP1)
DIMENS I(M XARRAY(200),AHSA(200)
TRAP1=0.0
IF(MI,F0,NE) RETURN
NFH(NF-1)
C INTEGRATE AHSA WITH RESPECT TO XARRAY FROM XARRAY(MI) TO
XARRAY(NF) BY THE TRAPEZOIDAL RULE
DO 1 J=MI,NF-1
TRAP1=TRAP1+0.5*(XARRAY(J+1)+XARRAY(J))*(AHSA(J+1)+AHSA(J))
RETURN
END
SUBROUTINE PLOTAL(X,Y,N,YLABEL,NY,XLABEL,NX,H,DOX)
DIMENSION X(N),Y(N),YLABEL(10),XLABEL(10)
COMMON HEAD(19)
SCALE THE Y VALUES
CALL SCALE(Y,N,10.,YMIN,DY,1)
DRAW THE Y AXIS
CALL AXIS(0.,0.,YLABEL,NY,10.,90.,YMIN,DY)
CALL SYMBOL(1,0,0,0,07,HEAD,0,75)
YIN=(0.-YMIN)/DY
IF(YIN.LT.0.)YIN=0.
IF(DOX.F0,0.)GO TO 16
NPI=(1.-0170DY)
XAXIS=(N+NPIN-1)/NPIN
DX=FLOAT(NPIN)*H
DRAW THE X AXIS
CALL AXIS(0.,YIN,XLABEL,NX,XAXIS,0,0,DX)
PLOT THE POINTS
XN=0.
CALL PLOT(XN,Y(1),3)
DO 15 J=2,N
XN=XN+DX
15 CALL PLOT(XN,Y(J),2)
MOVE PEN READY FOR NEXT GRAPH
CALL PLOT(XAXIS+2.,0.,=3)
RETURN
SCALE THE X VALUES
16 CALL SCALE(X,N,10.,XMIN,DX,1)
DRAW THE X AXIS
CALL AXIS(0.,YIN,XLABEL,NX,10,0,0.,XMIN,DX)
PLOT THE POINTS
CALL LINE(X,Y,N,1)
MOVE PEN READY FOR NEXT GRAPH
CALL PLOT(12.,0.,=3)
RETURN
END

```


APPENDIX 7

Theory of tension-time integral as defined by Starr (1951) for cases in which downward accelerations in excess of g occur.

It was shown (pages 66-67) that the tension-time integral, $\int_{t_1}^{t_2} T \cdot dt$, is equal to $-m \cdot g \cdot (t_2 - t_1)$ for any movement phase of duration $(t_2 - t_1)$ in which initial and final velocities are equal, and in which downward acceleration in excess of g do not occur.

Also, it was stated (page 69) that in those cases in which the downward acceleration becomes greater than gravitational acceleration, the magnitude of the tension-time integral (as defined by Starr, page 15) is no longer a fixed multiple of the movement time, but instead becomes a function of the acceleration.

Consider one movement cycle in which initial and final velocities of the moving body are zero, and in which downward accelerations greater than gravitational acceleration occur.

(Figure A1).

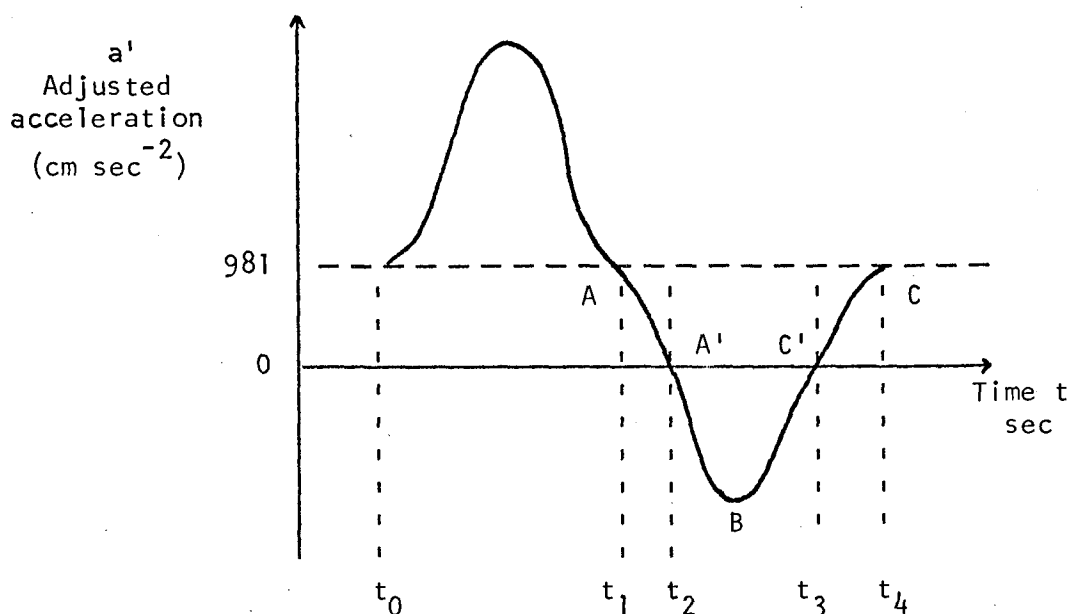


Fig. A1 Adjusted acceleration-time curve showing downward acceleration in excess of g .

Then the tension-time integral, $\int_{t_0}^{t_4} T \cdot dt$, is:

$$\begin{aligned} \int_{t_0}^{t_4} T \cdot dt &= m \int_{t_0}^{t_4} a' \cdot dt \\ &= m \left[\int_{t_0}^{t_2} a' \cdot dt + \int_{t_2}^{t_3} a' \cdot dt + \int_{t_3}^{t_4} a' \cdot dt \right] \\ &= -m \cdot g(t_4 - t_0) \text{ dyne sec} \end{aligned}$$

The tension-time integral as defined by Starr (page 15), TTI_S ,

is:

$$\begin{aligned} TTI_S &= m \left[\int_{t_0}^{t_2} a' \cdot dt - \int_{t_2}^{t_3} a' \cdot dt + \int_{t_3}^{t_4} a' \cdot dt \right] \\ &= \int_{t_0}^{t_4} T \cdot dt - 2m \int_{t_2}^{t_3} a' \cdot dt \end{aligned}$$

Since $\int_{t_2}^{t_3} a' \cdot dt < 0$, then

$$= \int_{t_0}^{t_4} T \cdot dt + 2m \left| \int_{t_2}^{t_3} a' \cdot dt \right|$$

$$= \left| m \cdot g \cdot (t_4 - t_0) \right| + 2m \left| \int_{t_2}^{t_3} a' \cdot dt \right|$$

That is the tension-time integral, as defined by Starr, exceeds by $2m \left| \int_{t_2}^{t_3} a' \cdot dt \right|$ the integral obtained when the peak downward acceleration does not exceed g , and becomes a function of the acceleration rather than a fixed quantity.

Since the acceleration-time relationship does not follow a standard functional form, exact quantification of this function is not possible. However, a rough approximation may be made:

From Figure A1, assuming ABC forms a triangle and that triangles ABC and A'BC' are similar, it is deduced that

$$\left| \int_{t_2}^{t_3} a' \cdot dt \right| = \frac{(t_4 - t_1) (a_{\max} - g)^2}{4a_{\max}}$$

Therefore

$$2 \left| \int_{t_2}^{t_3} a' \cdot dt \right| = \frac{(t_4 - t_1) (a_{\max} - g)^2}{2a_{\max}}$$

The increase in the integral is a function of both the time for which the downward acceleration in excess of g is maintained, and of the peak downward acceleration.

In Starr's study both upward-lifting and downward-lowering cycles

contained phases in which the downward acceleration exceeded g . From the Figure shown by Starr, it is estimated that the duration of both these phases was 0.4 sec. Further, it is estimated that peak downward accelerations were respectively 5×10^3 and 3×10^3 cm sec^{-2} ; the mass, m , was 10^3 gm.

Hence, the amount by which the total fixed-time tension-time integral for this task could be expected to exceed that obtained for work tasks not containing phases of downward acceleration in excess of g may be estimated as:

$$10^3 \left[\frac{(0.4) \cdot (5000 - 981)^2}{10^4} + \frac{(0.4) \cdot (3000 - 981)^2}{6 \times 10^3} \right]$$

$$= (648 + 273) \times 10^3$$

$$= 921 \times 10^3 \text{ dyne sec}$$

This approximates the increase of 1062×10^3 dyne sec which can be calculated from Starr's results (although again Starr's values are too big by a factor of 10^3).