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ABSTRACT

Analysis of the human and mechanical factors inherent in ergometry suggest many strategies for the improvement of experiments related to exertion. The resistive principles of gravitation, friction, elasticity, viscosity, magnetism, and inertia used in ergometers impose different restraints on experiments. The suitability of different resistive principles to differing experimental situations are discussed. The mechanical concept of work has led to confusion in the quantification of exertion, and units of impulse are suggested as preferable when irreversible transformations of chemical energy in human muscle are considered. The interaction of the subject's structure and the mechanics of the resistive devices requires the equation of subjects geometrically in both cross-sectional studies and within-subject comparisons. The differential rates of degradation of physiological and psychological adaptation (skill) over time allow the disentangling of the two sets of adaptations resulting simultaneously from practice. (EB)

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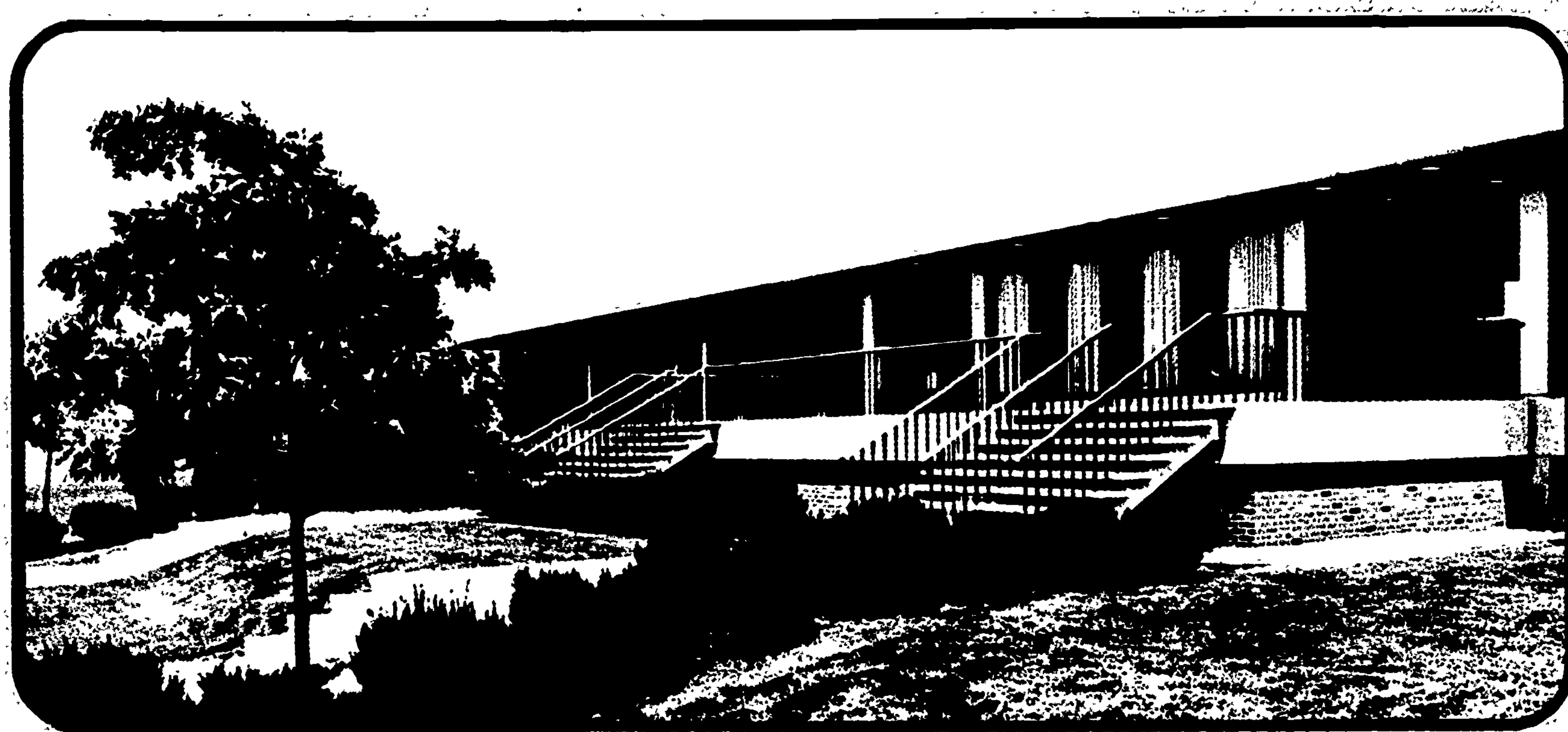

HUMAN AND MECHANICAL FACTORS IN ERGOMETRY

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in potential energy of the body; or they may act to change the rate of motion of the body or its parts resulting in a change in kinetic energy of the body-system. These motion-related forces alter the energy of the body and changes in potential and kinetic energy of known masses can be determined through analysis of their motion and are related directly to the actual work performed by the musculature. This type of analysis is arduous and it seems preferable to quantify the energy expenditure via respired gas analyses rather than the internal work done.

The work done on the surroundings may be quantified by ergometers which may be divided into two categories. In one category fall true ergometers and reciprocating motion ergographs which attempt to measure directly the work done on the surroundings. Into another category fall stepping, pack, running and treadmill tests in which measurement of the total work done on the surroundings and the work done in the system is usually not attempted. In the latter category, the energy expended is inferred from dependent variables like heart-rate and O_2 consumption. They are not true ergometers since work or impulse are not measured, but they are included here because of their ubiquity.

Those concerned with work measurement have sometimes assumed that compliance with a standard external load, or the production of a similar excursion from normal in a dependent variable, are enough to produce equivalence between different methods. The manner in which the work is done on the surroundings crucially affects the energy expended in the body-system and confounds the issue. A prime example of this

HUMAN AND MECHANICAL FACTORS IN ERGOMETRY[1]

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Abstract

Analysis of the human and mechanical factors inherent in ergometry suggest many strategies for the improvement of experiments on the exertion of human subjects. The resistive principles of gravitation, friction, elasticity, viscosity, magnetism and inertia used in ergometers impose different restraints on experiments. The suitability of different resistive principles to differing experimental situations are discussed. The mechanical concept of work has lead to confusion in the quantification of exertion, and units of impulse are suggested as preferable when irreversible transformations of chemical energy in human muscle are considered.

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INTRODUCTION

The researcher attempting to understand, measure and control human exertion confronts a complex system of physiological, psychological and mechanical events. The scientist using ergometric procedures observes and measures the events of exertion in an effort to obtain quantitative understanding of these events. This paper makes explicit some of the major mechanical assumptions tacit in contemporary ergometry and suggests means of avoiding possible confoundings. The first section of the paper deals with the mechanical factors of a man exercising against himself and/or his surroundings; the second part deals with physiological and psychological factors which affect performance

MECHANICAL FACTORS

Upon stimulation, chemical energy is used in muscles to produce force and heat. The heat raises the body temperature and is eventually transferred to the surroundings. Force, transmitted through the body, may do work on the surroundings, increasing the external energy. The relation of these events is shown in Figure 1.

Insert Figure 1 about here

The definitions used in this paper are presented as an appendix but a complete listing and description of physical quantities can be found in Richards, et al. (1960) and Beer and Johnson (1962). Here a human body is considered to be the system; everything not in the body is considered in the surroundings.

The quantity and rate of chemical energy utilized in the body-system has been related reliably to the quantities and rates of oxygen consumed and carbon dioxide produced (Consolaxio, Johnson and Pecora, 1963). Quantity and composition of respired gases can, after analysis and transformation, be used to express the total chemical energy converted over time. Energy is converted into heat and impulse (force for a period of time) which may or may not do work.

Force and Work

Forces produced in muscles during exertion are either transferred to the surroundings via the skeletal system or can be reacted against completely within the body, as in an isometric contraction. In both cases, force is produced at the cost of chemical energy, but in the latter no work is performed on either the body or its surroundings because the force is not associated with displacement. Energy can be expended and no work be performed.

When force production is associated with displacement, work may be performed on either the body, the surroundings, or both. Muscle forces may act to overcome internal resistance of the body such as viscous damping or friction producing heat; they may act to raise or lower the body or body parts against gravity resulting in a change in potential energy of the body; or they may act to change the rate of motion of the body or its parts resulting in a change in kinetic energy of the body-system. These motion-related forces alter the energy of the body and changes in potential and kinetic energy of known masses can be determined through analysis of their motion and are related directly to the actual work performed by the musculature. This type of analysis is arduous and it seems preferable to quantify the energy expenditure via respired gas analyses rather than the internal work done.

The work done on the surroundings may be quantified by ergometers which may be divided into two categories. In one category fall true ergometers and reciprocating motion ergographs which attempt to measure directly the work done on the surroundings. Into another category fall stepping, pack, running and treadmill tests in which measurement of the total work done on the surroundings and the work done in the system is usually not attempted. In the latter category, the energy expended is inferred from dependent variables like heart-rate and O_2 consumption. They are not true ergometers since work or impulse are not measured, but they are included here because of their ubiquity.

Those concerned with work measurement have sometimes assumed that compliance with a standard external load, or the production of a similar excursion from normal in a dependent variable, are enough to produce equivalence between different methods. The manner in which the work is done on the surroundings crucially affects the energy expended in the body-system and confounds the issue. A prime example of this assumption is the existence of a polemic as to whether using the treadmill or bicycle ergometer is the best method of measuring work. There are no general methods of ergometry. Each method has its limitations since any particular method of work measurement depends on a particular interaction of the parameters of internal and external work.

Resistive Principles

Since in many ergometric situations the same response by the subject is repeated rhythmically, the work done on the surroundings is assumed to be constant per unit response, making the number of responses or duration a parameter of the total external work done. However, there are other parameters of external work done since the reactive resistance, and hence the force, can vary according to displacement, velocity or acceleration of the point of application depending on the resistive principle employed in the ergometer, e.g., gravity, viscosity or inertia. To compound the issue, more than one resistive system can occur in a device. These resistive principles produce different effects on the work done against them as the physical parameters of the task are varied. For example, the work done against viscous resistance increases with the velocity of the moving parts. Thus, particular devices exact differing penalties should the experimenter fail to control critical parameters of the task.

Table 1 lists the various resistive systems, common ergometric devices employing them and the ideal relationships that exist between the resistive force and variation in either the displacement, velocity or acceleration of its point of application. The forces derived from the resistive principles are ideally related to their parameters as shown in the specific functions, but for particular applications other variables may significantly influence the resistive force. The first two resistances, gravitation and friction, are independent of motion, elasticity is dependent on displacement, viscosity and magnetic resistance are dependent on velocity and inertia is dependent on acceleration.

Insert Table 1 about here

Gravitation (Row 1 in the Table) offers resistance for a variety of tests which have in common the raising and lowering of mass in the gravitational field. The work done against it increases linearly with the increase in the upward displacement of the mass, and is independent of its velocity and acceleration. The work done against gravitation increases the potential energy of a mass in the surroundings, as in the case of an ergograph and/or the body-system itself in the case of stepping and pack tests. To quantify the work done against gravitation the weight moved is multiplied by its vertical displacement (mass x g) x D.

The mechanical concept of work is confusing when applied to work physiology (Starr, 1951). When a mass is returned to its initial position in a mechanical system with no residual momentum then no work has been expended since work expended on the surroundings during ascent is returned to the system on descent. However, the transformation of chemical energy to force in muscle is essentially irreversible and muscle tissue expends energy in retarding acceleration during descent which then appears as heat in the muscles. Thus, the energy expended during descent is added into, not subtracted from, the energy cost for the movement. Further, the maintenance of the system in an unstable position must also be considered since it costs energy to prevent the system being returned to a stable state by gravitation. This cost is a function of the force exerted and the duration for which it is maintained in the unstable position and, clearly, the ergometrist must consider the continual effects of gravitation on the performance of the subject.

Sliding friction (Row 2) is used in some cycle ergometers and depends on the subject driving a moving wheel against the resistance generated by a belt rubbing against the wheel. The pressure exerted by the belt normally to the moving wheel and the surface area in contact condition the magnitude of the resistance once the system is sliding and this resistance is independent of velocity. Thus, if the area of belt in contact with the moving wheel and the pressure between them can be controlled, the rate of movement developed by the subject does not influence the resistive force. The work done increases linearly with the increasing displacement of the sliding surfaces and can be controlled simply by counting the number of revolutions. Thus, sliding friction is suitable for studies where the resistive force is held constant while cadence is free to vary or is systematically varied.

Control of the drag (resistance) proved difficult until van Dobelin (1954) described the application of a sinus-brake to friction resisted ergometers. In the sinus-brake the drag of a friction-belt deflects a weighted lever, and its position displays the instantaneous drag permitting accurate calibration.

Row 3 in the table suggests a method of applying resistance through elasticity. The authors have not identified a formally described method of ergometry that uses this principle, but elastic strands or springs are used to provide the resistance in various commercially available exercise machines. Ideally the device would apply a resistance that increases linearly as the elastic device is deformed. Thus, the work done will increase curvilinearly as the amplitude is increased since both the force applied and distance moved are increased. If elastic resistance is used then the amplitude of movement must be rigidly controlled, but velocity and acceleration need only be standardized to control for energy expended in overcoming inertia of the effector limbs.

The resistance to motion by fluid viscosity can be used in ergometric devices (Row 4). The resistance to motion increases complexly with velocity to reach a limiting condition where the fluid flow is at a maximum and further increases in force applied do not increase the flow, i.e., the velocity of the point of application. Thus, this resistance parallels that produced by magnetic brakes in that an increase in cadence increases the work done. Hydraulic devices incorporating the principle of the shock absorber where a fluid is forced through an orifice, produce a rise in resistance with rate of flow which quickly reaches a terminal velocity. Once the maximal flow through the orifice is reached the force is dissipated via the incompressible liquid in the hydraulic system, in which case the force expended by the subject is independent of the motion of the device. In addition, the maximal rate of flow may vary significantly with changes in the temperature of the liquid. The force required to produce a given flow diminishes as the temperature of the liquid increases. Since repeated operation of the device may raise the temperature of the device, the use of hydraulic shock absorbers is made still more problematical.

Magnetic braking effects (Row 5) due to the generation of eddy currents in a rotor moving through a magnetic field produce resistance that is linearly related to the strength of the field and velocity of the conductor moving through the field. This braking method, though it provides a convenient system that is highly stable and is not subject to wear, carries heavy penalties if the subject does not maintain the required cadence unless it is allied to a servo-system. Consequently, as the change in work done generating the eddy currents is confounded with changes in the energy expended against inertia and other resistances within the system as cadence is altered by the subject. Thus, this method may be used only when the experimenter can assume given constant cadence.

Inertia (Row 6) which is a property of mass, provides a resistive force only to acceleration and the work done is the vector product of inertial resistive force and displacement. Work done accelerating a mass increases its kinetic energy and it is then said to posess momentum. Slowing a mass requires that its kinetic energy be reduced with the reduced fraction appearing as either work done elsewhere or heat. Inertia contributes handsomely to the cost of any reciprocating motion since a movement having been accelerated in the required direction then has to be decelerated as it approaches the end of its range and then accelerated back again in the opposite direction. Increasing the rate of reciprocation or cadence rapidly increases the forces involved and the system soon reaches its limit (Hubbard, 1957).

Inertia and Gravity as Confounding Resistances

Although inertia is physically independent of velocity and amplitude, the fact that the subejct has quite limited range of motion in any effector means that a constant velocity can be maintained only for a short distance by any limb; however, the maintenance of a constant velocity by the total body-system over a longer range requires repeated sub-movements that are essentially reciprocal. Thus, in walking, although some work is done against gravity as the center of mass rises and falls with each stride, the work is done primarily against inertia. As the horizontal velocity is changed, work is done against the inertia of the mass of the total body-system, and against the inertia of the limbs as they make their repeated sub-movements. In general, as horizontal velocity increases, the cadence of the reciprocal motions of the limbs increases and the work done against inertia is increased. This principle is the one used to increase the energy expended by subjects on treadmills. Apart from the heat generated by the impact of limbs on the belt, the friction between the foot and the belt in applying a force, and the disturbance of the air, clothing, etc., the energy expended is converted to heat within the body-system since no work has been done on the surroundings. The forces applied are mainly dissipated by overcoming the inertia and momentum of moving parts within the system. An experimenter concerned with removing from an experiment the variance in energy cost due to inertia, must control the mass and cadence of the reciprocating parts.

Running or walking up an inclined treadmill represents the addition of a gravitational element to the total work output since the subject must do work to prevent his mass moving downward. On the other hand, since every subject has mass no matter what the task, inertial resistances are added to any work situation providing the subject is changing the velocity of parts of his body-system. Thus, is stepping and pack tests accelerating and decelerating the parts and/or the whole system add to the energy expended against gravity.

In crank ergometers inertia also adds an initial load when masses have to be accelerated from rest at the beginning of the task. Differing initial accelerations will influence early responses to a task by significantly varying the work against inertia. The solution to this is to have the moving parts accelerated to the working rate by a motor which is disengaged as the subject approximates the correct cadence.

Servo-Ergometers

In general, each method has severe limitations in that variability of the subject's responses vary the energy expended and/or the work done on the surroundings. Two solutions to the variety of problems described above have been presented in the literature.

The first general solution has been applied to a crank ergometer by adding a servo-system that modifies the resistive torque as a function of the cranking cadence. The system exploits the use of an electrical servo-system to modify the field strength of an electromagnet as a function of the current generated by the rate of cranking. By setting these mechanisms in opposition, as cranking rate increases, field strength in the brake can be set to decrease, thus maintaining a constant time rate of work output or power. An example of this method has been demonstrated by Lanooy and Bonjer (1956) who produced an electrically-braked bicycle ergometer in which errors in cadence were compensated for by the variation in the resistance to motion. The advantages of this type of servo-device extend beyond the control of cadence errors by placing the relationship between the resistive torque and cranking rate under the control of the ergometrist, allowing power output to be studied independently of cadence.

Another servo-device has been used to control the velocity of a treadmill according to the position of the subject. In this case the opposite effect was produced in that the energy expenditure demanded of a particular subject by the device was matched to the immediate response of that subject placing the rate of energy expenditure under his control. As an extension of this principle, servo-systems that include the subject are driven by a cardio-tachometer in which the resistance of the ergometer is varied to produce a given heart rate. To the extent that heart rate measures energy expenditure this produces constant expenditure of energy rather than controlling the external work.

Impulse as a Unit

Another method to account for the external work done was suggested in principle by Starr (1951). He measured the energy transmitted to the surroundings instantaneously in force units as a function of the mass (weight/g) and the accelerations of the object moved. Starr suggested that the impulse (force x time) be integrated and energy expended expressed in dyne seconds. This avoided the difficulties of measuring the energy expended during static and eccentric contractions. This idea was taken one step further by Atkins and Nicholson (1963) who built a crank ergometer in which instantaneous torque was measured at the point of application by strain gauges. This method included in the work done all frictional losses outside the subject, and took into account the variation of the resistances from cycle to cycle as any of the parameters changed.

Since it is possible to integrate voltages produced by force-transducers over time, Starr's suggested units of dyne seconds become the preferred unit for measuring the work done externally without having to make assumptions about the constancy of the various parameters.

Torque metering devices only measure the component of a force acting tangentially to the axis of rotation and therefore do not include other components. Thus, it is possible, to take the worst case as an example, to apply a force in line with a crank at, say, top dead center, and do no work on the point of application. To avoid this problem in the external system the force applied by a subject should be in line with the axis of action of the transducer. Thus, a straight line motion device with the force transducer at the point of application seems to be the best true ergometer, i.e., a device for measuring the forces transferred to the surroundings. This when combined with O_2 requirement will provide a means for accurately disentangling the external, internal and basal requirements during a task.

It can be seen from the arguments developed above that a major difficulty stems from the inapplicability of the commonly used term "work" to much of the energy expended by the muscular systems, and from the irreversible nature of the transformation from chemical energy to force. Thus, chemical energy produces force or heat, which may be transformed to work, but a moving mass can not add useful energy to the body-system. It is probably best to avoid the use of the term work in the context of ergometry, or at least to ensure that the term is used to describe those events of exertion where displacement of mass is produced by the application of force. Finally, since the various methods used to induce exertion depend on specific interactions of the mechanical factors determining the resistive force, it is not possible to consider nominally similar energy transfer to the different kinds of devices as equivalent.

HUMAN FACTORS

The preceding section has been concerned with the delineation of the mechanical factors involved in measuring work done on the surroundings or in increasing the energy contained in the body-system. However, in ergometers proper, the satisfactory measurement of energy gained by the external system in the form of work or heat does not guarantee the satisfactory control of the energy expended in the body-system. The comparison of the relative adaptation to a given work stress by one subject with another, requires that the gross energy expended and measurable work done on the surroundings by the subjects must be strictly comparable. In experiments done on the same subject to compare change in adaptation to the task over time the repeated measures must be comparable. However, the methods used to ensure the exact measurement of work done on the external system do not necessarily guarantee that the energy expended by the subject within the system is also standardized.

Local Efficiency

The body is an assemblage of sub-systems acting upon each other and in sum producing effects that influence the surroundings or change the energy within the body. The sub-system that works against the surroundings or another segment of the body may be considered as a local system and transforms chemical energy into impulse (force x time) and to heat. The output impulse is a function of the extent to which the energy released within a muscle is converted to a force at its insertion.

Since force is a vector quantity it is resolved by its angle of insertion on the bone into effective and ineffective components at the point of insertion. Only the component acting normally to the bone induces a turning moment and the other acts along the bone to deform its shaft or joint structures and generate heat. It is that component of the force normal to the bone which may be considered effective in generating an effective impulse. The relative distribution of energy into an effective and ineffective component is primarily determined by the leverage structure of the individual, but the subject has available to him a range in which actions will not necessarily be equally effective. The skill of the individual in initiating action when the levers have reached an optimal position within the overall requirements of the system, can change considerably with practice.

Fenn and Marsh showed long ago (1935) that the faster a muscle shortens the distance between its origin and insertion, the smaller is the net force expressed as an impulse at the insertion. The assumption was that the difference between the gross generated force and that applied through its insertion is expended in overcoming internal resistances. At maximal velocity all the force generated internally within the muscle is expended on merely shortening the muscle and Hubbard (1960) described the mechanism whereby such actions result in ballistic responses.

The cadence at which the subject must operate, be it determined by the system or by the individual, very clearly influences the muscle efficiency. The faster the cadence the greater the acceleration required in the segments and the longer the initiating impulse and the more energy is consumed in overcoming internal resistances. Also the corresponding antagonistic impulse to first decelerate the limb and then accelerate it back also has to be longer. As the cadence rises reciprocal motions become less efficient and approach the limiting condition as the muscles work on faster moving segments. Thus it seems necessary on grounds of equating local efficiency to ensure that subjects being compared with themselves over time, operate at the same cadence.

A ballistic response involves a muscular contraction in which the impulse is generated during the early range of a response such that the limb moves along its path under its own momentum while the muscle either relaxes or continues to shorten without accelerating the limb. This runs counter to the common view of a muscle pulling on the limb for the duration of a particular action. Hubbard (1960) showed that the ballistic response was common, was the preferred response for skilled movements and had the additional advantage of muscle action during the time when the limb was either stationary or moving very slowly. Thus during ballistic actions the internal losses were minimized, and the net force applied during an impulse maximized. This clearly affects local efficiency providing the subject has available to him the choice of moving slowly. The extent to which the subject initiates an impulse at a point in time when the limb is moving slowly thus maximizing the net force, depends on his skill and structure. The skill of the subject, his ability to invoke the forces when they will maximize local efficiency, can change rapidly whereas the skeletal differences affecting the leverage system will change little and then only slowly.

Structure of the Subject

Changes in structure of an individual are likely to be small and differences in structure are controllable by the experimenter only to the extent that he can select for specific structures from the population. Variations between subjects are great and smaller subjects have been shown to be more efficient than larger subjects (Tappen, 1950; Wyndham, 1963) and in cases where the resistances to be overcome are provided by mass (i.e., gravitational and inertial) the larger subject expends more energy in doing the same work on the surroundings.

Standardizing the resistive mechanism and forcing different subjects of varying physiques to use it, materially changes the efficiency by varying the leverage systems of the effector parts and those supporting them. Thus, it is preferable to equate across subjects the dimensional relationships between the body system and the apparatus. For example, the length of the crank on a cycle ergometer is typically held constant from one subject to another, which means that a large subject works through a different range of motion than a small subject and may be forced to use different musculature. Between-subject comparisons are thus hazarded. This is supported by Rasch and Pierson (1960) who demonstrated that the force developed in any segment is a function of its position relative to those to which it is joined;

Bevegard, Freyschuss & Strandell (1966) who showed that efficiency fell when the smaller muscles in an effector were exerted; and Jeffery et al. (1965) who showed that foot-length had the highest of a series of very small but significant correlations (-.25) between anthropometric measures and tolerance to a submaximal bicycle ergometer test.

By not equating subjects geometrically, in addition to allowing otherwise controllable variation among the lever systems of the effector limbs, the energy expended by the interplay of the musculature participating in stabilizing the working segments is also changed. Dempster (1958) and Whitney (1958) have shown that the ability to exert force was limited by the capacity of the weakest link in the postural chain, not necessarily the main effector musculature. Similarly in repetitive movements the limiting factor will be the local endurance of the components in the postural chain. Applications of this effect have been shown by the fact that position in an industrial drilling task affected heart-rate (Horvat, 1968) and that the interplay of the postural muscles increases the cost, since when two tasks were performed simultaneously the cost was greater than the sum of the costs for the separate tasks (Andrews, 1966). The point to be derived from this is that the experimenter must, if he is to eliminate these alterations in the internal work, standardize exactly the positions of the subjects from subject to subject, and within-subjects from test to test. Thus, in a cycle ergometer it is not sufficient that only the saddle be adjusted but that each point of contact with the device be standardized so that subjects are equated geometrically.

Skill of the Subjects

Of that fraction of chemical energy converted to impulse by the local system, the effects can be divided into two categories: those that are desirable and advance the subject towards his intention, and those that are ineffective. The proportion of movements that are ineffective contribute to the inefficiency. This concept of the ratio between effective movements and ineffective movements corresponds very closely to the conventional concept of skill. Obviously as learning proceeds in a particular task the subject eliminates redundant or erroneous elements in the response thus becoming more efficient. This allows either a standard task to be accomplished with less exertion, or an increase in voluntary maximal efforts. For example, Shephard (1966) noted that the efficiencies in treadmill running and cycling changed with training while stepping efficiency did not. This suggests that the skills required for stepping already existed in his sample, but those for treadmill running and cycling did not.

The fact that the responses emitted by the subject during an ergometric test may change as a function of the change in skill of the subject confounds the assumption that differences in the subject over time or the differences among subjects may be ascribed to physiological factors. It is necessary for skill changes during an ergometric test to be minimized by considerable pre-experimental practice prior to transfer to the experimental condition. The difficulty with this procedure is that while the subject is adapting psychologically, physiological adaptations are also taking place. Two procedures seem possible under these circumstances. The ergometrist should utilize simple responses that have been practiced very extensively by the subject prior to the start of the experiment. For example, walking as a skill would seem to have been learned to the point where the adult subject is unlikely to acquire further skill as a function of walking, providing that the test approximates his normal velocity and gait. Thus, in comparisons across subjects it seems necessary to be assured that the task at hand has been learned to a point of common mastery among the subjects.

Alternatively it may be possible to capitalize on the fact that motor skills once over-learned are not easily forgotten and to a large extent are independent of the delay between acquisition and retesting (Adams, 1967). However, physiological adaptation seems to be dependent on the delay between the acquisition of the capacity and a test after a period of no training. These two different functions seem to suggest a way in which physiological and psychological adaptations to a task can be separated. After an initial period of practice which has produced an asymptote in the adaptation curve, the subject is then given a long period in which the task is not practiced. During the interval the over-learned motor skill will tend to be remembered while the physiological adaptation will tend to be degraded. After the period of detraining the subject can then practice again, with the secondary set of adaptations being ascribed to physiological adaptation.

Finally, the intravariances, the variability of a subject about his own mean score, in measures of performance on standardized tasks were shown by Wyndham et al. (1966) to vary up to 7.2%. Thus, even if all errors were eliminated, variation in performance of subjects about their own mean is considerable. This inconsistency is greater than that achieved in the objective measures in an ergometric system and suggests that within-subject variability is an important factor and requires multi-repeated measures designs to allow this to be evaluated and its effects partialled out.

The complex of mechanical and psychological factors add considerably to the problem of measuring the exertion of humans. The structure, the skill and the innate variability of the subjects all influence the ratio between the total energy expended and that transmitted appropriately to the ergometer. For improved quantifications of the events of exertion, different research strategies will be required to hold constant a variety of effects that are not usually eliminated by the ergometrist. It has been the purpose of this paper to raise only these issues. Unfortunately, still others, perhaps under the rubrics of social, motivational and personality factors, rear their heads in all experiments concerning the performance of subjects and will require elucidation by other authors.

LIST OF DEFINITIONS

The entries in parentheses are the same concepts expressed in SI (Systéme Internationale) units promulgated by the Conférence Générale des Poids et Mesures in 1954 (Anon, 1967).

<u>Force</u> is the action of one body on another body which changes or tends to change the state of motion of the body acted on. Force is a vector quantity with magnitude expressed in dynes (Newtons) with the direction and point or line of action specified relative to convenient spatial reference.

<u>Displacement</u> is the change of position of a point relative to a spatial reference and is a vector quantity with magnitude expressed in centimeters (meters).

<u>Velocity</u> is the time rate of change of diaplacement and is a vector quantity with magnitude expressed in linear distance per time, cm/sec (meters/sec).

<u>Acceleration</u> is the rate of change of velocity and is a vector quantity with magnitude expressed in linear distance per unit time squared, cm/sec^2 ($meters/sec^2$).

<u>Mass</u> is the quantitative measure of the resistance a body offers to being accelerated and is scalar. Force, mass, and acceleration are related by the familiar form of Newton's Second Law, $F = ma$. Mass is expressed in units of force divided by acceleration, dynes/ cm/sec^2 ($Newtons/kg/sec^2$) since a force of 1 dyne will acelerate a mass of 1 gm at 1 cm/sec^2 (1 Newton will accelerate a mass of 1 kgm at 1 m/sec^2).

<u>Work</u>, W, performed by a force, F, acting through a displacement, d, is the scalar product of the force and displacement, $W = Fd \cos \theta$, where θ is the angle between F and d. Note that work is a scalar quantity and that it depends on the relative orientation of F and d

as well as their magnitudes. The units of work, ergs, are force x distance, 1 dyne x 1 cm = 1 erg. (1 joule = 1 Newton x 1 meter).

Energy is a capacity to do work or transmit heat. Energy and work, both scalar quantities, are expressed in the same units, ergs (joules). Many forms of energy exist: mechanical, thermal, chemical and electrical energy are common. Mechanical energy has two forms: energy of motion, angular or linear kinetic energy; and energy of position, potential energy.

Impulse is the product of a force and the time for which it acts. Being the product of a vector, force, and a scalar, time, linear impulse in a vector quantity with units of force x time, i.e., dyne sec (Newton sec).

Momentum is the product of the mass and the linear velocity of a body. Mass is a scalar; velocity is a vector; and momentum is a vector quantity with units of mass x velocity, gm cm/sec (Kg m/sec). Remembering that 1 gm = 1 dyne cm/sec^2, note that the units of linear momentum can be converted to dyne/sec which are the units of impulse.

Power is the time rate of doing work and is expressed in units of work per time, ergs/sec (joules/sec or watts). Because work and time are scalar, power is a scalar quantity.

References

Adams, J. A. _Human Memory_, New York: McGraw-Hill, 1967.

Anon. The change to metric units. _Nature_, 1967, _216_, 1272-1274.

Andrews, R. B. The additivity of values of energy expenditure of simultaneously performed simple muscular tasks. _Ergonomics_, 1966, _9_, 507-515.

Atkins, A. R., & Nicholson, J. D. An accurate constant work rate ergometer. _J. Appl. Physiol._, 1963, _18_, 205-208.

Beer, F. P., & Johnston, E. R. _Vector Mechanics for Engineers: Statics and Dynamics_, New York: McGraw-Hill, 1962.

Bevegard, S., Freyschuss, U., & Strandell, T. Circulation adaptation to arm and leg exercise in supine and sitting position. _J. Appl. Physiol._, 1966, _21_, 37-46.

Consolazio, C., Johnson, R. E., & Pecora, L. _Physiological Measurements of Metabolic Methods in Man_, New York: McGraw-Hill, 1963.

Dempster, W. T. Analysis of two-handed pulls. _J. Appl. Physiol._, 1958, _13_, 469-480.

Dobeln, W. van. A simple bicycle ergometer. _J. Appl. Physiol._, 1954, _7_, 222-224.

Fenn, W. O., & Marsh, B. S. Muscular force at different speeds of shortening. _J. Physiol._, 1935, _85_, 277-297.

Horvat, V. M. Abstract of: Heart rate values for different work positions. _Ergonomics_, 1968, _10_, 717-718.

Hubbard, A. W. Homokinetics: Muscular function in human movement. P. 7-39 in _Science and Medicine of Exercise and Sports_, Ed. Johnson, W. R., New York: Harper and Bros. Publishers, 1960.

Jeffery, J. A., Jones, P. R. M., Ellis, M. J., Stone, P. G., & Worth, W. J. C. The somatic influence on work tolerance. Ergonomics, 1964, 7, 366. (full report available from Loughborough University of Technology, England)

Lanooy, C., & Bonjer, F. H. A hyperbolic ergometer for cycling and cranking. J. Appl. Physiol.,1956, 9, 499-502.

Rasch, P. J., & Pierson, W. R. Relationship between maximum isometric tension and breaking strength of forearm flexors. Res. Q. Am. Ass. Hlth. Phys. Educ., 1960, 31, 534-535.

Richards, J. A., Sears, F. W., Wehr, M. R., & Zemanski, M. W. Modern University Physics, Reading, Mass.: Addison-Wesley, 1960.

Shephard, R. J. The relative merits of the step-test bicycle ergometer and treadmill in assessment of cardio-respiratory fitness. Int. Z. Ang. Physiol., 1966, 23, 219-230.

Starr, I. Units for the expression of both static and dynamic work in similar terms and their application to weight-lifting experiments. J. Appl. Physiol., 1951, 4, 21-29.

Tappen, N. C. An anthropometric and constitutional study of championship weight-lifters. Am. J. Phys. Anthrop., 1950, 8, 49-64.

Whitney, R. J. Strength of the lifting action in man. Ergonomics, 1958, 1, 101-128.

Wyndham, C. H., Morrison, J. R., Williams, C. G., Strydom, N. B., von Rahden, M. J. E., Holdworth, L. D., van Graan, C. H., & van Rensberg, A. J. Inter- and intra-individual differences in energy expenditure and mechanical efficiency. Ergonomics, 1966, 9, 17-29.

Wyndham, C. H., Strydom, N. B., Morrison, J. R., Williams, C. G., Bredell, G. A. G., Peter, J., Cooke, H. M., & Jaffe, A. Influence of gross body weight on O_2 consumption and physical work capacity. Ergonomics, 1963, 6, 275-286.

Table 1. Parameters of the Resistive Forces Commonly Used in Ergometry

Resistive Principle	Common Ergometric Device or Procedure	Resistive Force Function	SI Units*
1. gravitation	Step tests Pack tests Finger & elbow ergographs	F_g = weight = f(mass x acceleration due to gravity)	kg x g
2. sliding friction	Friction drum ergometer	F_f = f(coefficient of friction of surfaces x normal force)	K_f x m**
3. elasticity		F_e = f(stiffness coefficient of elastic x displacement	K_s x m**
4. viscosity	Rowing tank	F_v = f(coefficient of viscosity x velocity)	K_v x m/sec**
5. magnetic	Motor resisted or magnetically resisted ergometers	F_m = f(velocity of conductor x magnetic flux density x charge)	m/sec x T x C
6. inertia	Treadmill running	F_i = f(mass x acceleration)	kg x m/sec

*SI Units are the units of the Systéme Internationale approved by the Conférence Générale des Poids et Mesures in 1954 to create a uniform system of units derived from the M.K.S.A. system (Anon. 1967).

**K_f, K_s and K_v are the coefficients of friction, stiffness and viscosity, respectively.

Figure 1

Simplified Schema of the Events of Exertion