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Human Strength: Terminology, Measurement, and Interpretation of Data

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Application of strength data to human engineering problems is often hampered by ambiguities of both terminology and data. This paper attempts to point out some of the problems. After defining "strength" and clarifying related terms, mechanical, physiological, and statistical implications of strength testing are discussed. It becomes obvious that strength data are fully relevant to human engineering problems only if the operator must exert maximal static muscle force; if submaximal forces are required, the applicability of strength data is very limited. Research is needed to establish relations between human static force capacity and the abilities to perform maximal or submaximal dynamic work. At present there is little evidence that static force data accurately predict dynamic performance.

INTRODUCTION

Measurements of static muscle force have, for many decades, been popular among physiologists, anthropologists, physical educationists, and human factors engineers. Isometric muscle tests are relatively easy to administer and the underlying mechanics appear rather simple. However, most work or sport activities consist mainly of dynamic efforts; "pure" isometrics are rare. Thus, it is of great interest to relate the capacity for static force exertion to the capability to perform dynamic work.

Many studies on muscular efforts suffer from one or several of the following shortcomings: (a) failure to define terms, or the inappropriate or imprecise use of terminology; (b) insufficient consideration of the biomechanics involved; (c) use of inadequate instrumentation; and, (d) failure to report clearly experimental procedures and statistical analyses. Such deficiencies make it very difficult to interpret experimental strength data and to apply them to the dynamic real-world situations.

TERMINOLOGY

The following definition of strength is proposed: *Strength is the maximal force muscles can exert isometrically in a single voluntary effort.* "Strength" refers to the muscular capacity to exert force under static conditions. Strength is measured as the external effect of internal isometric muscle efforts, modified by the mechanical advantages of the body members included. Dimensions of strength are *force* or *torque* × *time*, i.e., impulse over a given time, or force or torque alone if the effort is exerted instantaneously.

"Isometric" and "isotonic" refer only to the internal muscle effort; they do not describe the external effect or load. "Isometric" asserts that the length of the muscle stays constant during tension, but does not specify the muscle tension. "Isotonic" indicates that the tension of the muscle stays constant during its contraction, but does not specify its length.

"Effort" applies to both static and dynamic muscle activities. "Work" refers only to dynamic efforts that can be measured in units of "mechanical work."

"Dynamic" and "static" indicate whether motion accompanies muscle tension. A static effort results in force or torque exertion, but not in mechanical work. A dynamic effort results in mechanical work.

"Concentric" and "eccentric" refer to certain dynamic efforts: "concentric" indicates that the muscle shortens actively against a resistance: "eccentric" makes clear that the muscle is lengthened passively by an external force. "Phasic" may be used in lieu of "dynamic" when only a single contraction takes place.

The preceding definitions may help to avoid such ambiguous terms as "static work," "isotonic lifting," "dynamic strength" and similar paradoxes. To clarify further the definitions, certain terms and underlying mechanical principles will be discussed.

As defined, strength is exerted "isometrically" indicating that during the contraction period the length of the muscles involved is kept constant. Since muscle length does not change, attached body segments remain motionless. If there is no motion, all acting forces must be in balance; therefore, the word "static" may be used interchangeably with isometric. Both terms indicate that there is no limb motion but do not inform about the magnitude or steadiness of muscle tension.

"Isotonic" may be the most misused term in strength testing. It simply means "constant (muscle) tension" and, obviously, is neither an antonym for "isometric" nor does it describe the nature of an external load or resistance. Although theoretically not limited to this combination, an isotonic effort is normally found combined with an isometric force exertion, as in holding a weight motionless. Muscles are NOT strained isotonically when moving a body segment against a constant resistance; during the motion, the tension of the involved muscles changes with their changing length and with the changing mechanical advantages. If a constant mass is to be moved (as in weightlifting [Clarke, 1966]), this does not even mean that a constant force is required at the mass to effect its motion; the resistance offered by the mass changes with the changing velocity. There is really nothing isotonic happening at the muscles when moving constant masses. Whenever the term isotonic appears in the strength literature the reader should check whether "dynamic" is not really the appropriate term. If so, the kind of dynamic effort performed must then be explained.

Some ambiguities stem from discrepancies between physiological and mechanical semantics, as discussed by Brunnstrom (1966), Ramsey (1967), and Whitney (1958). In mechanics, "work" is defined either as the product of force and displacement, or, energetically, as the amount of change in potential or kinetic energy. If a human operator holds a weight isometrically, he does not "work" in the mechanical sense, since no motion occurs. He also does no "work" when lifting a mass and returning it to its initial location, since its potential energy is then the same as before. Still, both the static holding and the dynamic moving of the weight strain the operator physically and increase his metabolism, i.e., energy consumption. Koopman (according to Burger, *et al.*, 1967) consequently proposes that the word "effort" be used instead of "work" to indicate physiological strain.

In the case of dynamic efforts, the amount of energy exerted by the operator can easily be expressed in terms of mechanical work, if the absolute values of the energy changes are taken into account: e.g., to the positive work of lifting a weight could be added the negative work of lowering it to its original location.

There is no such easy solution for the case of static force exertion: this just is not "static work," as it is often incorrectly called. A static effort consists of exerting a force over a certain period of time without producing motion. The force may be integrated over the time of exertion and this integral may be called "impulse." This procedure is mechanically correct--but not always very meaningful. The result of the integration is a single numerical expression, concealing the well-known fact that over any given period of time a muscle force is not constant but may fluctuate considerably about a "mean" value (see Figure 1).

It appears that, for practical purposes, force integrals over periods of 1 sec. each are appro-

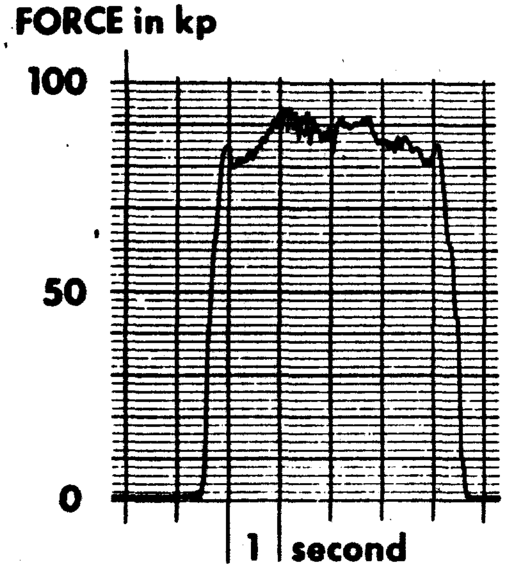

Figure 1. Record of a strength measurement. The subject was to exert a constant maximal force over a period of five seconds; he had no feedback of the actually exerted force. Note the fluctuations of the force during the supposedly constant phase, ranging from about 79 kp. (minimum) to 94 kp. (peak).

priate. Strength tests require force exertion of less than about 10 sec. to avoid muscle fatigue, as discussed later. Integration periods of 1 sec. each are short enough to reflect the more important force alterations during this test, yet are long enough to yield useful units of strength. A force integral over 1 sec. could be called "1-sec.-force" or "1-sec.-impulse" or "specific impulse." A short and handy analog to impulse may be "pulse." Thus "pulse" is proposed as a term in strength testing, signifying that force is integrated or averaged over 1 sec.

Generally, a muscle connects two body segments rotatable about a common joint. If the muscle is under tension, it applies torque to each segment. The magnitude of torque depends (1) on the amount of internal muscle force; (2) on the distance between the joint and the location of the muscle or tendon attachment to the bone, i.e. the lever arm; and (3) on the pull angle between the vector of muscle force and the limb (Brunnstrom, 1966; Elftman, 1966). Usually, neither pull angle nor lever arm are known. For practical purposes, the muscle is inaccessible and, therefore, the magnitude of internally developed muscle force cannot be measured directly.

However, the external effect of the internal muscular effort is measurable as the force exerted at a certain distance from the joint to an outside object. In the static case, this externally measured force is proportional (but not equal) to the internal muscle force. If lever arms and pull angles are known, the isometric muscle force can be calculated from the externally applied force.

For practical purposes, only the force exertable to an outside object is of interest. Since it depends on the strength of the muscle and on the prevailing mechanical advantages, the location of the force measuring device must be specified with respect to the next joint to make a strength measurement meaningful.

In a dynamic effort, the externally measured energy output at any given instant may not even be proportional to the internally developed energy. Muscular impulses accelerate and decelerate masses; this means storage and discharge of energy and inevitably delays and blurs the flow of muscular energy to the point of application. Since the mechanical advantages (lever arms, pull angles) are also changing during the dynamic process, calculation of the instantaneous internal muscle force from the measured external output is usually very difficult, if not impossible.

Prediction of dynamic performance from static strength tests would require, in terms of mechanics, the following procedure:

Step 1. The externally measured static force F must be modified by a constant factor C representing lever arms and pull angles to assess the internal muscle strength S:

$$F \times C = S \qquad (1)$$

Step 2. The static muscle strength S must be transformed into the muscular capacity D for dynamic exertion of energy:

$$S \rightarrow D \qquad (2)$$

Step 3. The capacity D has to be modified by a variable V, representing pull angles and lever arms as well as the amount of energy

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stored in or released from moving body parts. The variable V changes with orientation and speed of the limbs. The product of D and V indicates the external mechanical work W:

$$D \times V = W \qquad (3)$$

The first and third steps are theoretically simple, since they involve only transformation of one unit into another. Some complication, however, stems from the fact that the transformation factors are unknown and, in the last step, this factor is a variable. The second step is actually the most difficult; how to transform static muscle strength into the capacity to perform dynamic work? Though seemingly simple in physical terms, this poses a rather complicated physiological problem. Physiological processes such as oxygen supply to and waste removal from the muscle are rather different when accompanying short-time or sustained efforts, maximal or submaximal efforts, dynamic or static efforts.

Because of these mechanical and physiological considerations, it may be doubted (Kroemer, 1967) whether static strength tests can generally serve as accurate predictors for sustained dynamic performance even though they are somewhat loosely related by the fact that muscular efforts are involved in both.

MEASUREMENT OF HUMAN STRENGTH

Since the externally measured strength serves only as an expression of an unknown and unaccessible internal muscle force, and since the measured strength depends on the existing mechanical advantages; the location of the point of force application (i.e., the attachment of the measuring device) as well as the direction of the exerted force must be carefully selected and clearly described in the protocol. Taylor's (1954) finding that the mean "grasp" force of the hand is 90 lb. has been reprinted in several human engineering handbooks, but the parts of the palm or finger with which this force was transmitted, or the direction in which the force was exerted are unspecified.

Force is a vector. In addition to its magnitude, the location of its line of action and its direction must also be described. This is not done in some so-called strength tests (see, e.g., Clarke, 1966). The scientific value of such tests is rather dubious.

Some measuring devices are constructed so that they should be used only in a specific way; even so, a formal description of the way they are used is sometimes necessary. The various types of hand dynamometers, for example, measure the grip force exerted between the fingers and palm of the hand. If the dynamometer is attached to a stationary device, such as a table, instead of being held in the hand, the experimenter must take precautions to assure that the subjects squeeze with their fingers and do not pull with their arm and shoulder muscles (e.g., Smith and Edwards, 1968). Then too, some of the elliptical grip strength meters cannot be calibrated in the same way the subject actually applies the force, and can, therefore, yield only relative (not absolute) readings of "grip strength."

All measurements of muscle strength require that the outside resistance, against which force is applied, be larger than or at least equal to the maximal muscular force; nobody can exert a force larger than the reaction force available to him. Some published data are actually measurements of limited reaction force and are so described (Caldwell, 1962; Dempster, 1961; and Rohmert, 1960a); these data do not describe the intrinsic muscle strength of the subjects.

The definition of strength specifies that force be exerted in a "... single voluntary contraction." This limits the time during which strength can be measured to less than about 10 sec. (Caldwell, 1963, 1964; Rohmert, 1960b). Maximal muscular tension can be maintained without perceptible decrease for only such a short period of time. Muscular fatigue then sets in which reduces the exertable tension (de Vries, 1966; Lehmann, 1961, 1962; Scherrer, 1967). Even if force is required over only such few seconds, the exerted force is not constant but fluctuates in an irregular and unpredictable manner (Figure 1). These force alterations complicate the seemingly simple task of strength measurements.

Most instruments used to measure muscle

strength can be categorized as either "indicating" or "recording." All pointer instruments belong to the first group. They display only instantaneous measures of strength. While observing the oscillating pointer, the experimenter has to decide what to consider "the" score of the experiment: there is no way to check this index later. Since the needle does not come to a rest but oscillates continuously, the experimenter very likely will use the largest occurring deflection of the needle (the "peak" force) as the index for the subject's strength. On many instruments, selection of the peak is facilitated and almost dictated by a maximum indicator, a marker moved by the primary pointer and left at its largest deflection.

Recording devices are usually more expensive and not as easy to use as indicator instruments, but they yield a permanent record of the exerted force. If the force is traced over the total period of force exertion, the experimenter may check the experimental results at his ease; instead of being forced to rely on a hasty reading of a peak force, he can select the most suitable index.

Peak Versus Average Strength Scores

The experimenter has the choice between two types of indices to evaluate the outcome of strength tests. One is the peak value, i.e., the largest force amplitude observed during the test; the other is the "average" score, i.e., the result of an integration of the force recorded during a certain period of exertion.

In a recent experiment (Kroemer and Howard, 1968)* 22 subjects exerted horizontal push forces standing in two body positions. They either pushed forward with both hands while anchoring one heel against a footrest on the floor (Figure 2), or they pushed laterally with the preferred hand, bracing themselves with the opposite shoulder against a vertical wall (Figure 3). After a countdown of 3 sec., during which the subjects prepared for force exertion, they were asked to exert their maximal push force and to hold it at this maximum for 5 sec. (this is an isometric and, at the same time, isotonic force exertion).

The force curves, registered over the 5-sec. period of force exertion, were analyzed in several ways. The minimal force amplitude, occurring during the middle 3 of the 5 sec. of exertion, was compared to the maximal ampli-

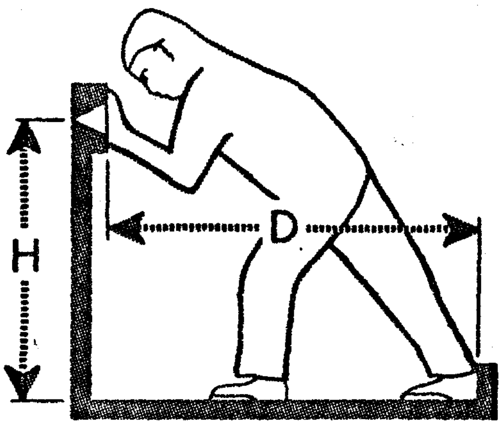

Figure 2. Forward leaning, push with both hands. Force plate adjusted to a height (H) of 70% and to a distance (D) of 80% of each subject's acromial height.

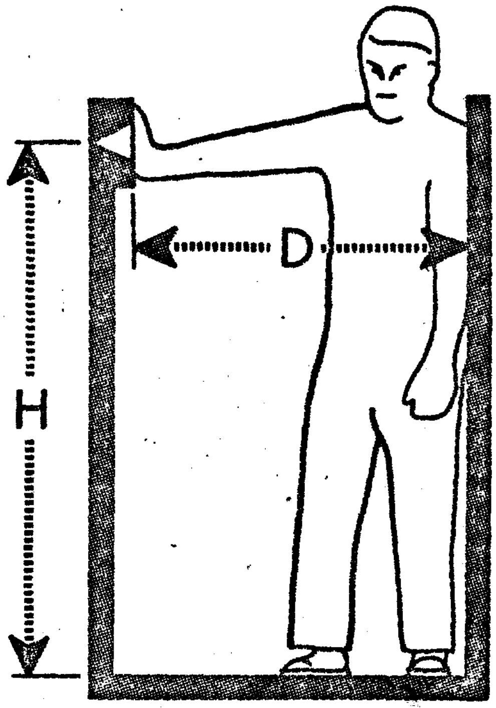

Figure 3. Laterally braced, push with the preferred hand. Force plate adjusted to a height (H) of 100% of each subject's acromial height and to a distance (D) of 80% of his lateral thumb-tip reach.

* should be 1970.

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tude recorded anytime during the 5 sec. The mean values for the minima were 40 kiloponds[1] (kp) for the two-handed forward pushes, and 44 kp for the one-handed lateral pushes. The respective mean peak scores were 56 kp for the forward push and 73 kp for the lateral push. The fact that the peak values were about 40 and 65%, respectively, larger than the minimal amplitudes indicates that the subjects could not, as requested, exert a constant (isotonic) push.

The "pulses" (forces averaged over 1 sec.) were also read from the registered force curves for each of the 5 sec. of supposedly constant force exertion. The average values of the first second were significantly lower than the mean forces of the following seconds, since in the initial phase of force exertion the subjects had to increase the exerted strength from the zero level. The average force over the total 5 sec. was therefore significantly lower than any of the pulses of the four last seconds and of the combinations of seconds 2 + 3, 2 + 4, and 2 + 3 + 4.

Had only an indicating instrument, especially one with a maximum indicator, been used in this experiment, the rather large mean peak scores would have been considered indicative of the subjects' strength. Had "pulses" been used, the subjects would have been considered much weaker. Either the mean peak or any of the average scores could have been called by the experimenter "maximal force."

The author examined 50 publications on human strength (excluding grip-strength studies), selected randomly from his library. The majority of these reports were published in the last 20 years. Although the topic of all these publications is "maximal" force capability, in only 7 of the 50 is it clearly stated which statistical index (peak or a certain average) was used to describe the subjects' performance. This leaves most of the reports with partly unexplained data.

How Strength Can Be Exerted in Many Ways

The force a subject exerts depends on his intrinsic muscular capacity, on his motivation to exert a certain portion of his inherent strength (Ikai and Steinhaus, 1961; Johnson and Nelson, 1967; Wilmore, 1968), and on the manner in which he exerts the force. This manner of exertion depends largely on the experimenter's instructions. If the experimenter does not prescribe a certain way to exert force, the subject selects one on his own, i.e., he instructs himself.

To assess the effects of different ways of exerting force the subjects in the study just cited (Kroemer and Howard, 1968)* were at one time instructed to exert force isometric-isotonically, and at another time to exert gradually increasing force in a self-paced manner until they reached their maxima, and then to release. These two ways of force exertion are chiefly isometric. Both took about 5 to 6 sec. to execute and they looked very much alike to an observer.

Since the application of ever-increasing force naturally leads to a peak value, this maximal amplitude was selected to serve as a basis for comparing the results of both ways of force exertion. The "increasing-to-maximum" way of force exertion yielded the following results: When pushing forward, the mean peak force was 67 kp (as compared to a mean peak of 56 kp with the more isotonic push); when pushing laterally, a measurement of 84 kp (as compared to 73 kp) was reached. These increases of about 20% in the forward pushes and of 15% in the lateral pushes are statistically significant and were the result of two different ways of exerting force that could not have been easily distinguished by an observer.

Of the 50 reports on muscle strength, from the author's library, only 17 contain sufficient information on how the subjects were instructed to use their muscles and/or how they actually exerted force. Taking into account that only 5 of these 17 reports (and 2 of the remaining 33) also contain information on the index (peak or average) selected to represent the subjects' performance, the author concludes that the great majority of these publications on strength are of rather limited value. To ensure that essential experimental parameters be reported, a checklist has been developed (Kroemer and Howard, 1968)*. It is reprinted at the conclusion of this article.

[1] kilopond (kp) = kilogram-force (kg_f).

* should be 1970.

INTERPRETATION AND APPLICATION OF STRENGTH DATA

The foregoing discussion indicates that strength data are interpretable and applicable for engineering purposes if "strength" is defined, and if the experimental and statistical procedures used in generating the data are explained. In this section, the significance of strength data for situations other than the original experimental condition are discussed.

The discussion incorporates the task of predicting values from data between which meaningful statistical correlations exist. Positive correlations have been found, for example, between muscle force capacities and body build, body weight, or stature (Damon, *et al.*, 1966; Laubach and McConville, 1966; Roberts, *et al.*, 1959; Tornvall, 1963). Unfortunately, most of these correlation coefficients, although statistically significant, are rather small and are therefore of only very limited value for practical purposes (Churchill, 1966). This is due to the fact that the square of the correlation coefficient is used in predictions; so a correlation coefficient of, say, 0.7 (which would be considered here as extraordinarily high) would account for only about half ($0.7^2 \approx 0.5$) of the variance of the predicted value.

The general question is to what extent experimental data on maximal static force capacity can be applied to real-world situations where maximal or submaximal static or dynamic efforts are required. To facilitate the discussion it shall be assumed that the physical properties of the operator population and of the experimental subjects are comparable, and that the work and experimental conditions are also comparable (Chapanis, 1967). The discussion will also be limited to the relations between strength and the operation of controls.

Strength Tests as Predictors for Static Efforts

Under the assumptions made, strength data from an experimental group would obviously be adequate to describe the maximal isometric forces that can be exerted by a corresponding operator group. For example, one would be able to use strength data to select suitable controls and to arrange them adequately—provided that the controls require application of static force of such a magnitude as to thoroughly tax the operator's strength.

Generally, however, force requirements (such as breakaway forces) are kept below the maximal capacity of the operator; otherwise the operator could not activate the control. As soon as it has been established that the operator's force capacity meets or exceeds the force requirement, strength ceases to be a relevant criterion. For example, man can exert his largest vertical pull forces with his hands by pulling upward with arms extended to a horizontal handle located below his hip height. Given that a control requires only relatively little vertical force, would one arrange it below hip height just because this location allows the largest static vertical pull force? Clearly, the amount by which a critical control force value can be exceeded is not the relevant arrangement criterion.

There is no reason to assume that the condition allowing man to exert his largest isometric force is also the condition most suitable for short-time exertion of submaximal static force. The criterion of maximal force capacity can only serve for checking whether an instantaneous force requirement can be met (if necessary, with a safety margin); if it is met, surplus strength ceases to be of any relevance.

However, if static force has to be maintained for considerable time, then it is of importance to consider by what amount the exertable force exceeds the required force. E. A. Mueller's experiments of the early 1930's implied that the length of time a force can be maintained depends on what fraction of the available strength must be exerted; the relatively smaller the force requirement, the longer it can be exerted. This relationship has recently been clearly demonstrated by Caldwell (1963, 1964), Caldwell and Smith (1966), Molbech (1963), Monod and Scherrer (1965), and Rohmert (1960b). The relationship between time and fractional strength is not linear. Figure 4 shows qualitatively that while total strength can be maintained only for a few seconds (that is how strength is defined), less than about 15 to 20% of total strength can be exerted for an "indefinite" time. Thus, it is advisable to select a condition in which the static force capacity exceeds by a large factor the required operational force if it has to be exerted for prolonged periods of time.

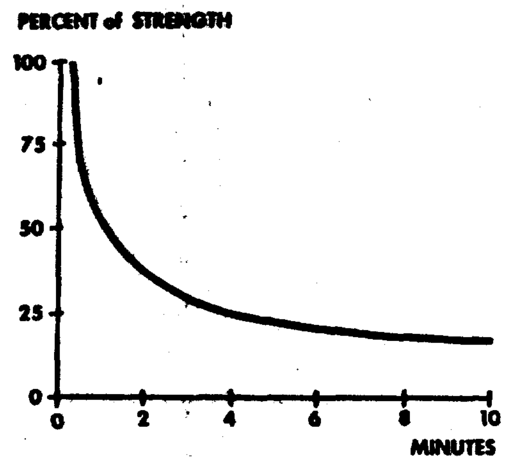

Figure 4. Endurance time as a function of force requirement. Schematically after Monod (1956), Rohmert (1960), and Caldwell (1964).

Maximum and Optimum

Is a condition allowing maximal exertion of isometric force also optimal for other than static efforts? This is often assumed to be the case, and this convenient assumption is made almost automatically whenever data on muscle strength are used to establish suitable work conditions. But, "maximum" is the greatest quantity possible, the upper limit of variation, while "optimum" is the best, the most favorable condition.

As "maximum" connotes an amount and "optimum" connotes a condition, it is obvious that these two terms refer to different phenomena. Optimum needs a further definition: optimum in what respect? With regard to muscular efforts, there are different optimal conditions; e.g., for static forces in contrast to dynamic work, for accurate movements in contrast to rapid motions, and for long-time power output in contrast to short outbursts of energy, etc.

In human engineering, an "optimal" work condition often is one in which the operator undergoes as little physical strain and fatigue as possible, so that he can perform his task for a long time without deterioration. Assessment of strain and fatigue then becomes an important experimental task in setting criteria for optimal force exertion.

There are at least five major methods whereby investigators have tried to assess the amount of physical strain and fatigue induced in man by muscular efforts. In this context, "physical strain" and "fatigue" are understood as closely related terms, indicating a physiological state of deteriorated capacity to perform physical work. Such strain or fatigue most likely is caused directly or indirectly by anoxia and accumulation of metabolites due to insufficient blood circulation in the employed muscles.

1. Measurement of fatigue of the central nervous system. Muscular fatigue is often accompanied by fatigue of the central nervous system. In this case, the thresholds of optical, acoustical, and tactile perception change (Rey and Rey, 1964, 1965; Rey and Stoll, 1965; Schmidtke, 1965). Unfortunately, these thresholds may be either lowered or raised depending on the type of work performed, on the amount of work done, and on the time elapsed between the cessation of the stress and the measurement of the threshold. Consequently, measurement of these thresholds as indicators cannot be considered as a generally applicable method, even though it is useful under certain conditions (Grandjean, 1967).

2. Measurement of energy consumption. Calculation of the energy consumption of a human operator during work relies on recording his oxygen intake and/or of the amount of CO_2 produced. This is a well-established and reliable method of assessing strain due to labor, provided that this strain is caused by dynamic muscle action. (e.g., Consolazio, *et al.*, 1963; de Vries, 1966; Dill, 1966; Karpovich, 1965; Lehmann, 1961, 1962; and Tornvall, 1963). Energy consumption measures, however, do not respond sufficiently to static tension of muscles. Unfortunately, such static effort is involved in almost all kinds of seemingly dynamic work, as parts of the body must be stiffened in order to provide counterbalance to the force output. The smaller the output of dynamic energy, the more important becomes the role of this static effort with regard to the stress of the operator, and consequently, the less reliable are data based on oxygen intake and CO_2 production.

3. Measurement of strain of the circulatory system. Physical stress on an operator generally results in, strain of his circulatory system. The circulatory system reacts to dynamic efforts of the muscles as well as to static efforts (Lehmann, 1961, 1962). Strain on the circulatory system can be observed by recording heart rate, which is a very sensitive indicator, responding to physiological as well as psychological stress. Psychological stress (for instance, excitement of the operator) can be completely independent of the physical work performed. So it may be difficult or even impossible to relate small differences in measured heart rate (of the order of five or less beats per minute) to actual differences in work load. Combined measurement of heart rate and energy consumption, however, appears to be a rather reliable and informative method, at least if the physical stress on the operator is not too small (Bouisset, *et al.*, 1965; Monod, 1967).

4. Measurement of subjectively perceived stress. Psychology provides a great variety of methods of assessing the strain of an operator (Adams, 1964; Ekman and Sjoeberg, 1965; Pearson and Byars, 1956; Schmidtke, 1965). Only a few of these methods have been related to physiological measurements. Experiments (Borg, 1961, 1962; Borg and Linderholm, 1967; Eisler, 1962; Frankenhaeuser, *et al.*, 1968; Hueting and Sarphati, 1966; Schmale, 1961; Schmale, *et al.*, 1963; Schmale and Vukovich, 1961; Schmidtke and Schmale, 1963) indicated that stress on the circulatory system of the operator appears to be closely connected with the subjectively perceived workload. The operator's subjective ratings of the amount of physical work performed were also found to be fairly reliable. Hence, it seems to be promising to rank work conditions with regard to the strain they induce in the operator either by measuring his heart rate or by asking him to rate the conditions according to the stress he perceives subjectively.

5. Measurement of work output (indirect method). If the amount of work output is not predetermined, stress on the operator may be judged by means of quantity or quality of his performance during the work period. A related method is to record the time consumed for accomplishment of the task or to measure the time during which the operator is able to continue his work without a break. These methods are easy to administer, but do not yield any direct indications on type and amount of the operator's strain or fatigue.

These remarks should show that there is no simple straightforward criterion for "optimum." The term may refer to very different phenomena, and may require rather complicated techniques for its assessment. So the convenient assumption that a condition which allows exertion of maximal static force is also optimal for performance of work is, in this general form, wrong.

Strength Tests as Predictors for Dynamic Efforts

As discussed in the first section of this paper, basic differences exist between the mechanics of muscle action in isometric and dynamic efforts. This makes it mechanically very difficult, if not impossible, to predict an operator's success in performing a dynamic task (for example, turning a crank) from a measurement of his static force capacity (for instance, holding a weight). It is true that holding a weight for a few seconds as well as turning a crank for the same time tax mainly the operator's arm and shoulder muscles. But these two actions are different from each other in several respects. In the static effort, the muscles involved are constantly strained over the total holding time, and no motion accompanies this effort; in the dynamic effort, tension and length of the muscles involved change with the motion of arms and of the crank. Such mechanical differences between static and dynamic efforts alone are sufficient to make it impossible to predict from the amount of weight the operator can hold for a few seconds the largest possible amount of energy he can transmit to the crank handle in the same time.

Physiological processes, mainly those connected with blood flow through the muscles, complicate the relations between strength and dynamic performance over extended periods of time. These processes can be very different when accompanying either short-time static or sustained dynamic efforts (Bonde Petersen, 1962; Monod and Scherrer, 1965; Purswell, 1967; Sharkey, 1966). During maximal static contractions, blood flow through the muscle is severely hindered or even completely cut off, but in dynamic work it may be facilitated and increased. Oxygen supply to the muscle and waste removal from it, accomplished by sufficient blood flow, and other physiological factors rather than short-time brute muscle strength, determine how long an operator can continue to work dynamically.

An example using data contained in the draft for the second edition of the *Human Engineering Guide to Equipment Design* (Morgan, Cook, Chapanis, Lund, 1963) may illustrate what relations can be expected between static strength and the ability to perform dynamic tasks: 119 lb. were found to be the mean "maximal" weight of boxes 26 X 11 X 7 in., to be lifted with both hands 3 ft. from the floor (19 students; Emanuel, *et al.*, 1956). Seventy-one to 96 lb. were reported as mean "reasonable" weights of 12 X 12 X 6-in. boxes, to be lifted with two hands 3½ ft. from the floor (75 students; Switzer, 1962). Based on their experimental findings as well as on a literature survey, Snook and Irvine (1967) concluded that 50 lb. are the maximum "permissible" weight to be lifted by unselected adult male workers.

There is really no way to tie these values for dynamic work to seemingly related static force data, obtained when subjects pulled upwards isometrically with both hands at a horizontal bar at about mid-thigh height. Approximately 10,000 British workers exerted on the average 363 lb. in static backlift (i.e., in attempting to straighten the slightly bent back; Cathcart, 1935). Approximately 900 United States Air Force personnel appeared to be much stronger when using seemingly the same type of bar: They exerted a mean static pull-up force of 520 lb. in backlift, and as much as 1,480 lb. in leglift (Clarke, 1945). (These data are reprinted in the first edition of the *Human Engineering Guide to Equipment Design* (Morgan, *et al.*, 1963). No explanation for the surprising differences in strength is offered there, nor are the reasons obvious from the original reports.)

This example is a rare one since the maximal static scores as well as several "optimal" dynamic scores have been experimentally determined; so both kinds can be compared. This example illustrates some of the difficulties encountered when trying to relate maximal-static-force scores to operational conditions by trying to derive from the "maximum" the tolerable, the permissible, the reasonable, or whatever may be the "optimum" for the given situation.

In addition to professional muscle physiologists, many students and teachers in physical education are, for obvious reasons, conducting studies to test the efficiency of static and dynamic training, to compare the results of both techniques, and to point out their relative merits. Hunsicker and Greey (1957) give the classic review of the literature; the majority of the newer publications are listed by Asmussen, *et al.*, (1965), Belka (1968), Caldwell (1964), Caldwell and Smith (1966), de Vries (1966), Kroemer (1969), Lehmann (1961, 1962), Rohmert (1968), and Sharkey (1966).

Despite many excellent studies, and although some rather interesting results have been obtained, generally applicable and practically meaningful relations between static and dynamic performance have not yet been established. Sharkey (1966), in his comparison of static and dynamic exercise, described the state of the art as follows:

> The fact that ambiguity still exists in this area is evidence of the confusion that results when dissimilar quantities of exercise, performed in two types of contractions, using a number of different contraction durations, repetitions, and sets are compared.[2]

Here is a field where further experimentation is definitely needed, and where theoretical as well as practical results can be obtained simultaneously.

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[2] Page 520.

The problem of the relationship between maximal strength and submaximal dynamic work played a role in a study by Kroemer (1966). Since this study was published in German in a report difficult to obtain in the United States, it is reported here in some detail. The question was posed:

What is the optimal arrangement and mode of operation of cranks and levers to be operated continuously in to-and-fro movements–"optimal" being defined as causing the least possible strain and fatigue of the operator, as indicated by his heart rate and his subjective ranking of the experimental conditions.

The radii of the cranks and levers used were of two lengths, 15 and 30 cm. The resistance torque to be overcome ranged from 2 to 6.8 meter-kilopond (m.-kp.). The resistance was constant during the travel of the control in one direction, and was then reduced to about 15% during the control return in the opposite direction to the starting position. The controls were operated to and fro either 10 or 20 times per minute, through angles of 90° or 180°. The moment of inertia of the rotating parts of the experimental equipment was about · 0.6 cm.-kp.-sec.^{2}. Each test session for each condition lasted ten minutes.

In preliminary studies all work conditions that were distinctly uncomfortable and strenuous had been ruled out. For the remaining more favorable conditions (among which the best were to be found), the controls were adjusted to different positions within the reach capabilities of the subjects. The type and size of the controls, the location and size and direction of the travel of the handles, and the torques of resistance were varied systematically. The subjects, who were all right-handed, sat on a stool and operated the controls with their right hands. They had to maintain the required angular orientation of their bodies in relation to the axis of rotation of the controls, but were allowed to choose the distance from this axis. It was assumed that, given the choice of distances and body postures, they would select those most comfortable and adequate to the task. It was felt that experiments with only two well-trained subjects would provide useful data; altogether, eight male subjects took part in the experiments.

Schmale's experiments (1961, 1963) and preliminary studies had shown that heart rate increases from resting level and that the subjects' judgments of the strain perceived while working provided useful and reliable criteria for the section of optimal work conditions. For the latter criterion the subjects were asked to say which one of a pair of work conditions they "liked better" after they had completed test sessions of ten minutes each. The test sessions were so arranged that the conditions to be compared preceded as well as followed each other at least once per subject.

Figure 5 shows the different locations of travel of the control handles in the first series of experiments. Here, the handles traveled through a vertical plane passing through the subject's right shoulder, parallel to his mid-sagittal plane. The radius of the cranks and levers employed was 30 cm., the sweeping angle 90°, the torque of resistance 6.8 m.-kp., the frequency of operation ten times per minute.

In a second series of experiments, the handles traveled in a horizontal plane at about waist height. In a third series the handles traveled in a vertical plane, parallel to the frontal plane of the operators. Here, the torque of resistance had to be lowered to 5.3 m.-kp. in order to induce about the same strain in the subjects as in the first experiments.

In the last series of experiments, the angle swept by the controls was 180° (see Figure 6). As in the first series, the handles traveled through a vertical plane passing through the subject's right shoulder. The radii of the cranks employed were 15 and 30 cm. (Levers could not be used since they do not permit a 180° rotation without changing the grip of the hand.) The frequency of operation was 10 and 20 times per minute. The torques of resistance ranged from 2 to 6.8 m.-kp. The subjects were both sitting and standing.

The results of this study indicate:

1. In agreement with findings by Borg (1962), Frankenhaeuser, *et al.* (1968), Hueting and Sarphati (1966), Schmale (1961), Schmale, *et al.* (1963), and Schmidtke and Schmale (1963), similar rankings of the experimental conditions were obtained when based either on the judgments voiced by the subjects or

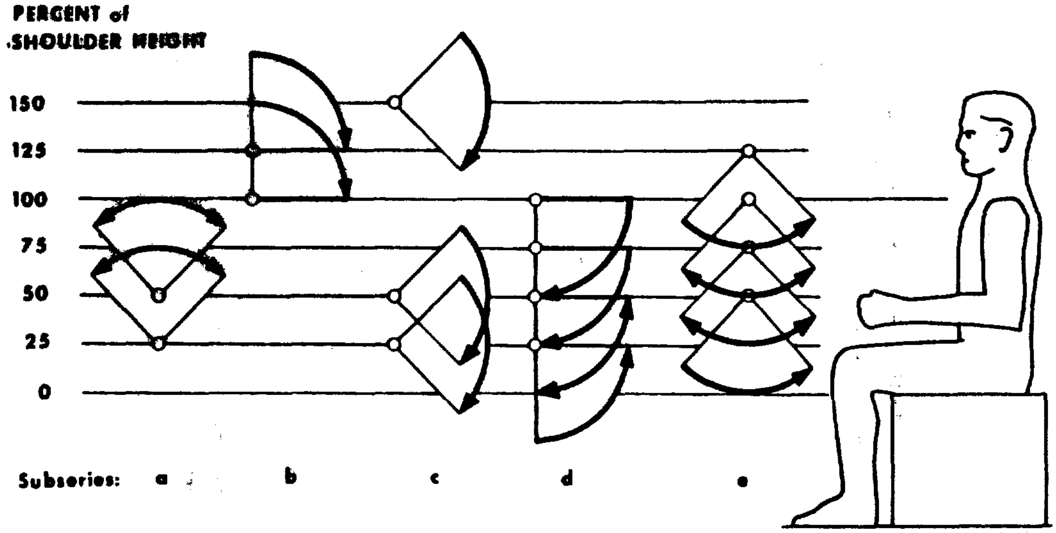

Figure 5. Ninety-degree to-and-fro motions with cranks and levers of 30-cm. radius. Orientation of the sweeping angle constant in subseries a–e. *Axis of rotation adjusted in steps of 25% to the subject's shoulder height when sitting.*

according to changes in their heart rates. This should encourage further evaluation and utilization of combined psychological and physiological experimentation.

2. The best range for location of cranks and levers to be operated continuously to and fro is in front of the sitting or standing operator so that the handle travels at about waist height in the sagittal plane passing through his shoulder.

(a) If the control has to be rotated 90° against resistances of about 5 to 7 m.-kp., operation is least fatiguing by pulling hori-

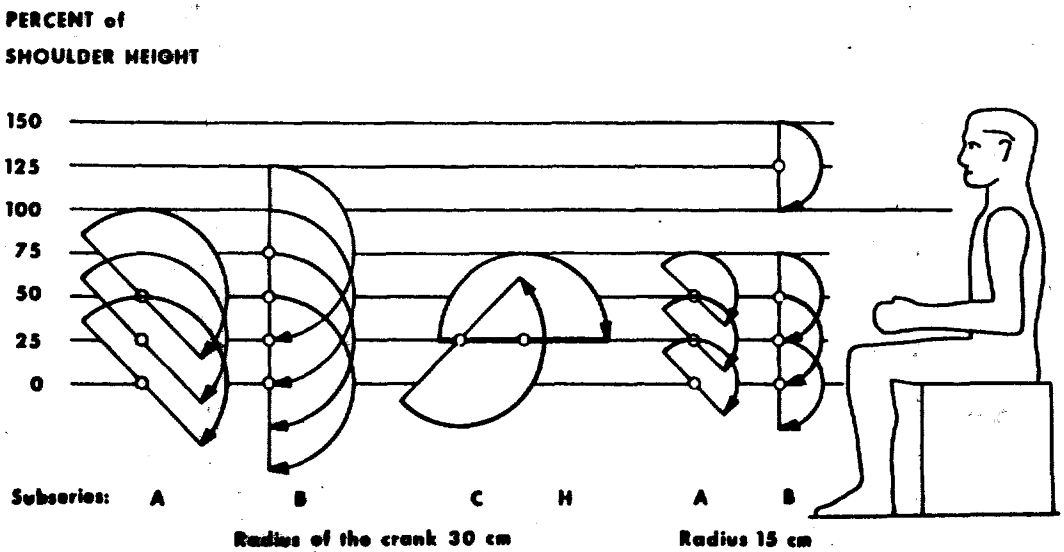

Figure 6. One-hundred-eighty-degree to-and-fro motions with cranks of 30- and 15-cm. radius. Orientation of the sweeping angle constant in subseries a *and* b. *Axis of rotation adjusted in steps of 25% to the subject's shoulder height when sitting.*

zontally against the major resistance and then pushing back to the starting position against a reduced resistance.

(b) If the control has to be rotated 180° against resistance of about 3.5 to 7 m.-kp., operation is least fatiguing by pulling horizontally in the beginning and downwards in the final phase and then pushing back to the starting position against a reduced resistance.

3. Control positions found to be optimal (least straining) for these dynamic efforts are not the same positions allowing exertion of maximal static forces (as shown, e.g., by Caldwell, 1959; Hunsicker, 1955; and Rohmert, 1966).

In very slow motions the force exerted at every instant may be interpretable as a succession of static efforts (Bender and Kaplan, 1966). This is certainly not so in more rapid motions, which is not only deducible from theoretical mechanical considerations, but has also been shown experimentally. Kogi, *et al.* (1965) demonstrated that the forces exerted dynamically during cranking (at 60 rpm) are much lower than those exertable statically measured with the crank handle fixed at intervals of 30° through the total cycle. This was found in cranking against small resistances as well as when very large amounts of power (up to 37 m.-kp/sec) had to be exerted; even then the highest force exerted dynamically was only about 70% of the static force applicable in the same crank position. Through the rest of the revolution, the ratio of dynamic to static force was still considerably smaller.

These theoretical considerations and experimental findings lead to the following conclusion: There is a difference between static force and dynamic work, and optimum is not the same as maximum. Therefore, measurements of man's maximal static forces do not provide a sufficient basis for the layout of controls which must enable an operator to perform dynamic-submaximal work with the least amount of physical strain.

SUMMARY AND CONCLUSION

Since direct measurements at the muscle are very difficult, strength is commonly assessed as the static force that can be exerted externally at a measuring device. The amount of exerted force does not depend only on the intrinsic muscle strength and the given mechanical advantages, but also depends to a large degree on the subject's motivation. The subject's force exertion may be greatly affected by the experimenter's instructions. The experimenter also affects the results by selecting the index representing the subject's performance. As demonstrated, the same performance may be graded very differently, depending on the selected index.

A general lack of standardization hampers comparisons and interpretations of the results of strength studies conducted by different researchers. The main shortcomings are discrepancies between terminology in physics and physiology (what is "static work"?); inadequate use of terms (what is "isotonic strength"?); use of measuring devices that cannot be calibrated satisfactorily (some of the elliptical grip strength meters) or that do not record permanently; lack of consensus on how to control motivational factors, and how to instruct the subjects (what is a "maximal" effort?); and lack of consensus on the strength score to be used as the statistical index (peak or some average score).

In application of strength data the assumption is widely used that a condition enabling man to exert the largest static force is also optimal for submaximal force exertion. The validity of such a general assumption is rather questionable. Nevertheless, this generalization is part of another dubious rule of thumb. Here it is assumed that a condition enabling man to exert the maximal static force is also optimal for performance of dynamic work.

Mechanical and physiological considerations as well as experimental evidence show why predictions of dynamic performance from static strength tests generally are not very reliable, although musuclar efforts are involved in both.

To supply the human engineer with reliable and comparable data on muscular strength, a general agreement (standardization) is desirable pertaining to terminology, instrumentation and recording methods, instructions given to the subjects, control of motivational factors, and index selection representing the subjects' performance.

It is not only the ambiguity of some published data, or the great variance of experimental data that makes application of strength information difficult; there is also a gap in the data, since strength studies have been conducted mainly with highly selected groups; e.g., with students, primarily with physical education students. Very little is known about the force capabilities of women, or of elderly people, or of the population in general.

Finally, and most important from a practical point of view, the relationship between maximal static force capacity–strength–and the ability to perform maximal or submaximal amounts of dynamic work must be established.

CHECKLIST

A checklist has been prepared as an aid for reporting how force is measured, where force is applied, what body parts are mainly involved and what posture is employed, how the subject is instructed to exert force, what role motivational factors play, and what index is selected to rate the subject's performance. There are interactions between apparatus, subject, experimenter, and environment that cause some redundancies in the list. For example, the subject's body posture as well as the magnitude of exertible force will be affected by the support (reaction force) available to him. Such cross-references are useful since they point out the multiple effects of a single factor.

The following list has been compiled for force measurements. It can easily to adapted to tests of torque and work, etc.

A. Measuring Device

1. General identification
   a. function
   b. model, manufacturer
   c. last calibration
2. Attachment of measuring device to the subject
3. Output-readout (digital, analog)–units read
4. Other (specify)

B. Location of the Force Vector

1. Static force exertion (no motion): coordinates of the point of force application and direction of force
2. Dynamic force exertion (motion):
   a. coordinates of the path of the force application
   b. direction of force along the path
   c. motion on the path (temporary location, speed, acceleration)
   d. masses accelerated or decelerated
3. Other (specify)

C. Subject

1. Drawn from what population
2. Anthropometric data
3. Other (specify)

D. Posture of the Subject

1. Coupling of the subject to the measuring device (see A2)
2. Body parts and muscles chiefly used
3. Body posture during force exertion
4. Body support–reaction force available
5. Other (specify)

E. Method of Force Exertion

Exact wording of the instructions given to the subject, or (especially if no specific instructions given) how force was actually exerted. In particular:

1. Requested magnitude of force (all-out effort or submaximal)
2. Requested manner of force exertion
   a. how to build up force
   b. what to do after requested magnitude has been reached
   c. how long to exert force
   d. whether muscle length is kept constant during exertion (isometric)
   e. whether muscle tension is kept constant during exertion (isotonic)
3. Time interval between subsequent tests
4. How many repetitions
5. Practice/training
6. Other (specify)

F. Motivational Factors

1. Selection of subjects
2. Voluntary/required participation
3. Mode of payment
4. Knowledge of the purpose of the experiment
5. Knowledge of the experimental procedure
6. Feedback of performance
7. Supervision during the experiment
8. Stimulating factors, such as encouragements, rewards, competition, spectators
9. Restraining factors, such as danger, fear of injuries, adverse environmental conditions, fatigue, lack of interest, spectators
10. Other (specify)

G. Selection of Performance Score

1. Amplitude-dependent value (maximum, minimum, etc.
2. Time-dependent value (at or over a specified time)
3. Other (specify)

See bottom of page 313.

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In reprinting the CHECKLIST, the final sentences of the original text were inadvertently omitted. Thus, after G.3. on page 311, the following should be inserted:

"We propose:

Use the peak (i.e., the largest instantaneous amplitude) occurring any time during the exertion period if force is exerted for less than 3 seconds.

Use the average of the middle second if force is exerted for 3 or more seconds. However, use the peak (see above) if the score exceeds 110% of the average at any time."