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THE STUDY OF MONKEY, APE AND HUMAN MORPHOLOGY AND PHYSIOLOGY
RELATING TO STRENGTH AND ENDURANCE

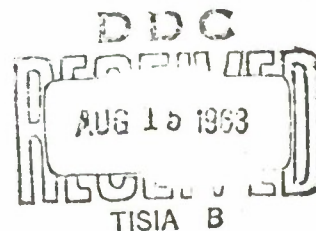
PHASE I: THE RELATIONSHIPS OF HUMAN SIZE TO STRENGTH

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FOREWORD

For some years, the writer has been interested in the determinants of human strength, as part of the broader problem of the determinants of all aspects of primate form and function. The basic formula was first derived and empirically tested in 1958, while a subsequent portion of this study was conducted during the writer's tenure as a National Science Foundation Science Faculty fellow at the University of Chicago, 1959-1961.

The writer is indebted to Lt. Col. Hamilton H. Blackshear, USAF,MC, Maj. James Cook, USAF,VC, and Maj. Robert H. Edwards, USAF,MC of the Aeromedical Research Laboratory of Holloman Air Force Base, New Mexico, for their very helpful cooperation and encouragement in the study here reported.

ABSTRACT

Actual relationships of human size to strength have remained undetermined despite decades of research by many investigators because the determination necessitates valid theoretical formulation and selection through three essential criteria of a proper sample of subjects for empirical testing. The formula is: $\text{strength} = k \cdot \frac{\text{Vol. (Wt.)}}{\text{Ht.}}$ · Champion weightlifters satisfy all criteria, and, by minor adjustments for sample size and skeletal proportion, specific lifts can be predicted within ounces.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

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1. INTRODUCTION

For maximal clarity from the outset, it seems best to start with definitions of at least the terms defining the scope of this paper. The term size is here employed in a rather general sense and refers to: any physical dimension of the body, such as height, shoulder breadth, and arm girth; quantities representing the composite of two dimensions, such as body surface area and cross-sectional limb or muscle area; and those attributes resulting simultaneously from three linear dimensions, such as limb or entire body volume and weight.

The term strength likewise requires clarification. As here employed, strength will of course be limited to a physical, mechanical usage, referring to force. In the case of organisms, contractile force, the sole function of muscles, is considered. It should be emphasized that strength is often mistakenly confused with some related concepts: work, which is the action of force through a distance; power, which is the rate of doing work; and endurance, which refers to relative ability to maintain a given power through time.

Absolute strength refers either to the contractile force developed by a muscle fiber along its main axis (absolute fiber strength) or, as a step removed from this most basic application of the term strength, to the entire contractile force of the muscle along its main axis, that is, upon the tendons (absolute muscle strength). It might be observed that the axis of most muscle fibers may be very different from the axis of the entire muscle, so the muscle's absolute strength is not simply the summation of that of its constituent fibers. Third, internal leverage strength is the strength of the muscle acting upon the body itself, with greater or lesser effect depending upon its leverage and its angle to the main axis of the segment of the body resisting motion. One or occasionally more than one fulcrum may intervene between the proximal and distal tendons of the muscle. The fulcrum may be intermediate between the tendinous attachment (force) to the moving member and the center of gravity (resistance) of the moving member (a first order lever system), as in the action of the triceps in extending the antebrachium. Or the tendon -- force -- may be intermediate (a third order lever), as in flexion of the antebrachium by the biceps. Theoretically, the center of gravity of the moving member -- resistance -- may also be intermediate (a second order lever), but because motion would be so relatively restricted by this last arrangement, it occurs in the human body only in a few contestable cases, such as plantar flexion of the feet raising the body on tiptoe if the ball of the foot is regarded as the fulcrum.* A little further consideration of the mechanics

* Perhaps the only incontestable case of a second order lever in humans is one discovered by the writer (Edwards, 1963): in performing the rather difficult feat of lifting his body suspended by one arm in rope-climbing or in a one-arm pull-up, the athlete (or arboreal primate) accomplishes apparently the major portion of the lift by the biceps, arising proximal to the shoulder-joint center of resistance.

involved reveals that internal leverage strength is inversely proportionate to the maximum translocation of the body segment moved; so in evolution greater mobility is almost always achieved primarily at the cost of lessened internal leverage strength, except where the increased mobility is accompanied by proportionately larger or more "efficient" muscles. Fourth, external leverage strength is that force applicable to an object outside the body.

Measurement of the absolute strength of muscle fiber bundles and even of individual fibers in a living human is conceivable but has not as yet been done. As recently as 1947, Cureton (p. 362) stated that "there is no direct way to measure the absolute muscle force in any living human being," but about that time significant strength studies of amputees with cineplastic tunnels through various muscles were being initiated (e.g., Ralston et al., 1949). Only through the indirect method of measuring the resistance (weight of the moving segment) and its acceleration is it possible to calculate approximate internal leverage strengths; but the maxima of such forces differ appreciably from those under isometric (static) conditions, while the analysis of moving bodies is further complicated by the fact that maximum force varies greatly with relative muscle length (Maxton, 1944).

External leverage strength is that most readily and frequently measured. To the external resistance can be added the resistance of the bodily segments upon which the muscles are acting. But much additional computation is required, and the resulting combination of internal and external leverage strength is, if anything, less meaningful empirically (for practical considerations, that is) and not necessarily more meaningful theoretically. So in this paper "strength" will normally refer to external leverage strength.

It should be noted, however, that despite the emphasis in this paper on external leverage strength, internal leverage strength will have to be considered to explain the former's relationships to size. In fact, for each of the four "levels" of manifested force except the first (absolute fiber strength), satisfactory analysis must include consideration of the immediately underlying form of strength.

That in most human muscular performances there are three distinct maxima should also be recognized. First, there is the maximum strength which a human is willing to exercise voluntarily, a maximum limited by consciously and/or subconsciously inhibiting fear of injury, as especially noticeable in a back-lift test of a subject with a history of frequent backaches. Second, an often appreciably higher maximum is the force attainable under normal conditions without fear-of-injury limitation. Finally, under exceptional conditions, such as grave personal danger or rage, a third and generally much higher maximum can be achieved, with epinephrine (adrenalin) release and associated physiological changes.

Further complicating the proper interpretation of strength data is the fact that for no group of muscles are the three performance levels sharply and very consistently distinct. For example, with the exercise of greater "will-power" or with greater experience in a given strength test, it is possible to exceed not only the normal limitation of the first maximum but, with the "firing" of an abnormally large percentage of muscle fibers, the

second maximum as well. To determine the true relationships of human size to strength, subjects must be chosen who manifest the same maximum (first, second, or third) under test conditions, or, if scores are intermediate between two maxima, approximately the same proportionate divergence from one of these. Since psychological factors, including history of previous injuries, result in extreme variability in the proportionate difference between the first and second maxima, the subjects (at least for the muscle groups to be tested) should be those whose performances are not markedly reduced by the first limitation. Furthermore, it would seem best to test only the second maximum among subjects all of whom, through maximum motivation and optimum experience, had pushed this maximum about as high as possible, to be discussed subsequently.

Since this paper involves a consideration of man's form and function, the process by which such an effective human form and function originated might be considered before proceeding further. Until a century ago, almost all considering this problem, at least from Aristotle on, accepted varying teleological explanations; man was considered the most important "final cause" or goal -- the end-product -- of the creation of the universe, for such an enormous number of highly useful attributes possessed by humans could not be explained by chance or by any other mechanical process. Not until Darwin (and Wallace) proposed evolution through the mechanism of natural selection did it become possible to explain the selective survival of the progressively more fit, resulting in, to some extent, an ever closer approach to "the best of all possible worlds" for the more fortunate survivors. Thus, otherwise infinitely improbable forms and functions of all organisms almost perfectly suited to general environmental conditions and specific ways of life became not only possible but inevitable through the operation of natural selection.

With the advent of human culture, however, selective pressures became progressively reduced, and departure from optimum form and function in humans was initiated. Furthermore, through the same protective aspects of culture, man's form and function became progressively variable, both through increasingly varied genotypes and increasingly varied intergroup and intra-group environments. In correlating human size and strength, this extreme variability must be considered.

A question distinct from that of accounting for the historical development of human form and function, both of which are still near-optimal, is whether human form and function must obey all aspects of universal laws. "Dreams apart, numerical precision is the very soul of science, and its attainment affords the best, perhaps the only criterion of the truth of theories and the correctness of experiments" (Thompson, 1942, p. 2). Continuing the repugnance of Pascal and Goethe to treat organisms as physical mechanisms, most zoologists are even now "deeply reluctant to compare the living with the dead, or to explain by geometry or by mechanics the things which have their part in the mystery of life" (*ibid.*, p. 3). Yet during the nineteenth century each physical and chemical process previously considered unique to living organisms was invalidated, until all life scientists must now concede that "no physical law, any more than gravity itself, not even among the puzzles of stereochemistry or of physiological surface action or osmosis, is known to be transgressed by the bodily mechanism" (*ibid.*, p.13).

The greatest reluctance to apply universal laws to organic form and function occurred understandably in the case of that form considered somewhat intermediate between the natural and supernatural worlds, mankind itself (White, 1949). But at present few physiologists, anthropologists, or even psychologists would deny the applicability of such laws to all observable aspects of man. The progressively adopted view among scientists has been that not only living organisms in general but man himself is a part of the natural world; he obeys natural laws on both the physical and organic levels. As one exemplification, scores of studies for more than a century have attempted to induce the theoretical relationships of human size to strength and then to demonstrate that these actually apply empirically, or to approach the problem deductively by observing detailed masses of size and strength data and then attempting to relate the two theoretically. That previous studies have failed to produce a mechanistic solution to the problem reflects the failure to recognize certain essential and interacting principles. Hence, they have not arrived at a theoretical formula for relating strength to size. Even the detailed studies which have come closest to achieving the solution terminated with little more than unanswered queries, as will be shown subsequently.

2. PREVIOUS RESEARCH ON HUMAN STRENGTH

Scientific study of human strength was apparently initiated by de la Hire (1699). Many additional studies were reported during the nearly two hundred years which elapsed before Francis Galton (1881; 1883) undertook that which remains the most extensive strength study to date; as Chairman of the Anthropometric Committee of the British Association for the Advancement of Science, he collected strength test and body measurement data on thousands of British subjects from 1875 to 1881. In this country, Kellogg (1896) developed the universal dynamometer, while the Harvard anthropologist Sargent (1897) developed the Intercollegiate Strength Test. Martin (1921) originated "resistance strength tests," with muscles in isometric condition resisting an increasing pull against them. The tensiometer was helpful for such performances with minimized bodily movement, while even more accurate strain-gauge dynamometers, which record changing electrical resistance when stretched, were developed in the 1930's. More detailed consideration of the history of research on human strength by the hundreds of investigators who have contributed to this field and of devices for testing strength can be found in the reports of Krakower (1937), Cureton et al. (1941), Cureton (1947), Hunsicker and Donnelly (1955), H. Clarke (1956), and Hunsicker and Greey (1957).

Many aspects of the research methodology have developed more slowly than the apparatus employed. For example, only gradually did the necessity for standardized test conditions become apparent, as in the need for adjustable hand-grip dynamometers. The extreme variation resulting from differences in angles between the body portions involved was not fully recognized until quite recently (Cureton, 1947, pp. 363-365). Test scores with different devices, with seemingly only negligible variations in position and bracing, have been shown to be very inconsistent (Mathews, 1953). Also generally unrecognized has been the extent of variability in performance of the same subject on the same apparatus on different days; only recently is the need for testing reliability through intercorrelations of repeated tests becoming recognized (D. Clarke, 1960).

Formal laboratory procedures have developed such an aura of scientific respectability that most researchers have failed to see, in their frequent preoccupation with new testing apparatus, that many organized sports and the athletes trained in them provide incomparable data for the solution of many problems of muscle strength, speed, and endurance. A notable exception to the foregoing statement is the physiologist Hill, who wrote: "The processes of athletics are simple and measurable and carried out to a constant degree, namely to the utmost of man's powers: those of industry are not" (1927, p. 3). Relatedly -- since athletes represent an atypical population -- is the fact that, although many decades have been required before even the most competent investigators have come to recognize the need for truly random sampling of subjects in much research, apparently few if any have quite fully recognized the desirability of an extremely deviant group of test subjects for certain physiological studies. A few published indications of at least partial appreciation of this fact exist, however. "[Physical] condition may vary so greatly, that a consistent relationship between strength and muscle size could be formed only in a trained group" (Curceton, 1947, p. 365). A recent study of 62 "dominantly mesomorphic" male physical education majors 20 to 26 years of age revealed .52 and .42 correlations between "tensed flexed" brachial girth versus shoulder flexion and elbow flexion strength; "it is questionable if similar results would be obtained with a random sample of college students" (H. Clarke, 1954, pp. 141 and 143).

To determine the relationships between size and strength in man, there are at least four requisites. The first essential is a population in which all readily determinable environmental factors are virtually constant. That experienced weightlifters constitute such a population, in which nutrition, exercise, experience in the required performance, and motivation are quite constant, has gone virtually unnoticed. Second, only one investigator, the anthropologist Tappen, who also clearly recognized the first requirement, has, to the writer's knowledge, indicated possible realization that only those athletes with the best performance records thereby manifest near-equivalence in the other determinants of ability, including genetic and other idiosyncratic factors, such as disease history, the influences of which are usually not quantifiable or in most cases even recognizable: "The study of championship lifters should provide an assemblage of individuals approximating greatest strength potential and to some extent eliminate the problem of evaluating the amount of training the lifter has had" (Tappen, 1950, p. 49). Third, there seems to be no recognition in the literature of another phenomenon crucial to the demonstration of the precise role of size in determining strength -- that the effects of the strength-determining factors, individually and collectively, are limited asymptotically. Finally, although a few students of strength have understood its theoretical relationship to size as being determined by principles of geometrical similitude, none of these recognized any of the other three essentials. It has been necessary to utilize all four of these understandings simultaneously to solve the problem with which this paper is concerned, a problem which has resisted proper interpretation for two centuries. Only weightlifting performances -- which, it should be emphasized, are executed under almost ideally standardized "laboratory" conditions -- feasibly satisfy all requirements for the determination of the relationships of human size to strength.

Many previous studies have related human strength to species (primarily comparing man and chimpanzee), race, body-build, age, sex, intelligence, nutrition, health, posture, exercise, experience with the strength-testing performance, bilateral differentiation, one group versus other groups of muscles, endurance, speed, athletic performance, personality, and culture. But only one of the correlates of strength—body dimensions — has for two centuries received the primary attention of scores of investigators. Despite the fact that none of the other factors listed has been considered at all adequately, it would be anticipated that at least this sole very intensively considered factor, anthropometric data, would long ago have been related properly to human strength; but such is far from the case, for these relationships have remained an enigma.

Some investigators have found a close correlation between weight and strength, especially among children (Martin, 1918, pp. 72-77). The apparently highest reported correlation coefficient between weight and strength -- .6582 for hand-grip strength (Everett and Sills, 1952, p. 162) -- can be accounted for, the present writer would suggest, by the additional factor that hand length, and therefore leverage advantage, is also positively correlated with weight.

Dozens of studies have affirmed a fairly marked positive correlation between stature and strength. The Harvard physiologist Martin (1918, p. 77) even asserted that his data on children approximated his calculation that strength should theoretically vary with the cube of height; however, Martin's formula represents a general misconception, as will be shown. But when weight is factored out, the correlation with height is either approximately nil or negative, for, the writer would explain, stockiness is markedly advantageous to strength theoretically, but its advantage is, in many Western nations with abundant food, almost counterbalanced by correlated increased adiposity.

Among other bodily measures which have been correlated with various manifestations of strength are chest breadth, bi-acromial diameter, bi-iliac diameter, bi-zygomatic diameter, leg length, hand width, biceps muscle thickness, upper arm girth, forearm girth, and fat-corrected thigh girth. Much closer correlations with strength would have resulted had the dimensions been squared, but in no case was the significance of doing so appreciated. Relationships between strength and surface area, body-segment volume, muscle mass, and fat mass have also been considered.

Since it constitutes the research most comparable to and significant to the present study, the previously mentioned paper by Tappen (1950) should be considered more fully. Detailed anthropometric data were collected on 46 of the 57 contestants in the 1947 National A.A.U. Weight Lifting Championships, and 43 were somatyped by W. H. Sheldon and W. M. Krogman, using photographs. One "outstanding lifter" was significantly an achondroplastic dwarf. With body-weight plotted directly against lift-weight, similar regression lines were determined for the three standard lifts -- the press, snatch, and jerk, to be described in a subsequent section -- but the graphed values did not very closely coincide with these straight lines. Then the best 1947 European and World Championship scores were analyzed, indicating again "that smaller men

can reach a greater peak of relative strength than can larger ones" (p. 54). Height was also correlated with lift-weight. After weight was factored out, height correlated $-.34$ with press values, but $.14$ with snatch and $.37$ with jerk lifts. With height factored out, weight was then correlated ($.76$, $.51$, and $.34$). Lift-weights were also correlated with each other: press to snatch ($.91$), press to jerk ($.85$), and snatch to jerk ($.97$). Finally, correlations with such measures as shoulder breadth and arm length, both especially significant to press scores, were computed.

3. MUSCLE MORPHOLOGY AND PHYSIOLOGY AND THE THEORETICAL RELATIONSHIP OF SIZE TO STRENGTH

Among the three types of muscles -- visceral (smooth or involuntary), cardiac (heart), and skeletal (striated or voluntary) -- the 220 human skeletal muscles (actually almost double that number, since the vast majority are paired) constitute some 36 per cent of the body weight in females and 42 per cent in males (Greisheimer, 1955, p. 151). Removal of the connective tissue (fascia) surrounding the muscle reveals that the organ is divided into large bundles, which in turn are composed of smaller primary bundles (fascicles). Each fascicle has many muscle fibers of two or three different sizes, separated from and yet bound to each other, as are the fascicles, by connective tissue with "displacement membranes," which permit high mobility between fascicles and between fibers and which may contain significant quantities of adipose tissue (Höncke, 1947, p. 32). Each fiber constitutes a multi-nucleated cell, surrounded by tough, elastic membrane (sarcolemma), and round or oval in cross-section. The striated fibers, generally about $50\ \mu$ (microns) but occasionally in excess of $100\ \mu$ in diameter, range in length to 13 cm. (Höncke, 1947, p. 15) and usually terminate at one end at least in a tendinous attachment to the skeletal structure (Scheer, 1953, p. 298). Each of the approximately 250,000,000 striated fibers in the human body (Fulton, 1950) contains hundreds or thousands of myofibrils some 1 micron wide; the myofibrils are separated about 5 microns from each other by undifferentiated cytoplasm (sarcoplasm), which contains mitochondria and glycogen granules. Myofibrils are in turn composed of the ultimate contractile structures, myosin and actin filaments (micellae), which are $.005$ to $.025\ \mu$ in diameter and are apparently spirally intertwined in bundles (Höncke, 1947, pp. 25-28; Best and Taylor, 1955, pp. 714-715; Huxley and Hanson, 1960, pp. 189 and 197-203).

The muscles are well supplied with blood vessels, with as many as 4000 capillaries per square millimeter (Schneider, 1941, p. 226).

Somatic efferent nerves penetrate the sarcolemma and contact the sarcoplasm at the motor end-plate; depending upon the size of the muscle and its required precision of movement, each nerve fiber supplies 2 to 2000 muscle fibers which, grouped with the supplying nerve, constitute a motor unit (Basmajian, 1962, p. 10). It has generally been considered that each muscle fiber has but one end-plate, but some investigators have reported two or more (Höncke, 1947, p. 35).

Ever since the classic studies of the tongue by Galen almost two millenia ago (Bastholm, 1950, pp. 84-87), it has been recognized that muscle only functions by contraction and relaxation. Significantly, except for the lower modulus of elasticity of mammalian fibers, man's muscle function does not differ fundamentally from that of the frog, temperature considered (Höncke, 1947, p. 196). Following end-plate excitation, contraction occurs through the interaction of actomyosin and adenosine triphosphatase, with energy from creatine phosphate hydrolysis and, ultimately, from glycolysis or the oxidation of a substrate (probably a carbohydrate) in the muscle (Scheer, 1953, pp. 296-317). Glycolysis provides energy for the rebuilding of creatine phosphate, with the production of pyruvic acid. Pyruvic acid in turn is partly oxidized to CO_2 and H_2O to provide energy to restore the remaining pyruvic acid to glycogen.

To provide for increased energy demands for oxygen, many capillaries expand and some apparently generally closed become functional, facilitating as much as a 750-fold increase in blood flow (Schneider, 1941, p. 226). With long-continued exercise ("training"), the number of erythrocytes and their contained hemoglobin may increase 25 per cent.

But in virtually all metazoa, natural selection has secured a mechanism for temporary activity at a rate of energy expenditure far in excess of the maximum oxygen providable, more than a tenfold excess in the case of sprinters, for example (Hill, 1927, p. 28). Then pyruvic acid is converted to lactic acid (as much as 0.32 per cent concentration in all muscles), which accumulates until oxygen is supplied for reconversion, ultimately, to glycogen (Hill, 1927, p. 32). The limitation on the "oxygen debt," as much as 19 liters (Schneider, 1941, pp. 62-63), inevitably reduces the average speed with vigorous athletic activities (such as running) as the duration is increased -- with curves whose lower limiting asymptotes for speed, as the present writer would express it, approximate the speed maintainable without any oxygen debt (Hill, 1927, p. 43).

Yet even with vigorous exercise only a fraction of the fibers of the muscles most used are "fired" at any one time, normally. Single fibers function on the "all-or-none" principle, but greater stimulus intensity results in greater muscular contraction, apparently because of different firing thresholds for individual fibers (Scheer, 1953, p. 298). Also, contractions from rapidly repetitive stimuli exhibit the phenomenon of "summation," with forces several times as great as those of single twitches, even if the single stimulus is maximal and excites all fibers (Fulton, 1950, p. 128; Scheer, 1953, p. 302). Even only a double discharge from a motor neuron results in more than twice the tension of a single twitch (Gordon and Holbourn, 1949, p. 33). If the stimulus is maintained at high frequency, tetany results, generally with tension three to four times that of a single stimulus (Höncke, 1947, p. 194). Epinephrine release results in the dilatation of skeletal muscle capillaries, increased muscular tension and endurance, and liberation of sugar

from liver glycogen; the effect of norepinephrine is fairly similar but less pronounced (Barcroft and Konzett, 1949, pp. 201-203; Brown, Goffart, and Dias, 1950; Best and Taylor, 1955, pp. 827-837). Increasing knowledge of the effects of epinephrine helps to explain the long-recognized effects of excitement on performances involving strength or endurance (Martin, 1921, p. 469). From available experimental evidence, it has generally been concluded that maximal tensions resulting from voluntary contractions are much smaller than those produced by maximal artificial stimulation, thus tending to protect humans from likely damaging extreme contractions (Ralston et al., 1949, p. 532); but some recent studies indicate much less limitation on extent of voluntary contraction (Basmajian, 1962, pp. 79-80), as the major data to be considered in this paper would also seem to imply.

Maximal tension can be produced when muscle length (which may shorten to 50 per cent) is 100 to 125 per cent of equilibrium length (Höncke, 1947, p. 195) or 60 to 80 per cent of maximum stretched length (Fulton, 1950, p. 123). In part, the increased tension is due to reinforcement by proprioceptive impulses in stretched muscle, in which the threshold for effective cortical stimulus is also lowered (Basmajian, 1962, p. 60). The maximum force applicable to an external resistance occurs at an optimum "compromise" between the skeletal angle at maximum muscle length (generally the maximal tension length in the living human) and that when the muscle/bone angle is 90 degrees (Bowen, 1923). Tension is reduced with increases in speed of muscle-shortening, so maximal tension is developed when this speed is zero, that is, when the contraction is isometric (Wilkie, 1950); therefore, the movement involved in weightlifting causes this activity to be an imperfect indicator of maximum strength, while on the other hand the relatively slow movements should result in fairly insignificant and quite proportional reductions. But the rapidity with which the force is developed has virtually no effect on the force produced (Ralston et al., 1949, p. 531).

Muscles function most efficiently at approximately their resting length (Fulton, 1950, p. 124) and develop maximum power at any given initial length when the resistance is between 25 and 40 per cent of the maximum which the muscle can sustain (Ralston et al., 1949, p. 532). Starr (1951) has proposed a formula for equating static (isometric) "work" and dynamic work, based upon equivalence of muscular energy consumption.

Despite the reservations of some (Haxton, 1944), it appears that the tension developable by a muscle is -- somewhat analogous to the tensile strength of a wire of given material -- proportionate to cross-sectional area when all other factors are equivalent, that is, when all components of the muscle are geometrically similar. Certain modifications of a muscle's components result in greater exorable force, but at the proportionate expense of mobility. With corrections for the obliquity of muscle fibers, Haxton computed an average value of 3.9 kg/cm² for human ankle flexors, while Ralston et al. (1949) found values of 2.38, 1.31, and 1.63 kg/cm² for the biceps brachii, triceps, and pectoralis major of amputees.

In considering the further application of mechanical principles to man, it may be observed that Archimedes recognized that the surface or other equivalent areas of geometrically similar objects increase as the square of a linear dimension, while volume increases as the cube. Galileo first formulated the general principles of geometrical similitude, in which he demonstrated that the various stresses and strains in organisms (and therefore their responses to them) do not remain proportionate to mass as body-size varies (Thompson, 1942, p. 27). Borelli (1685) studied "the proportions between the necessary muscular strength and the points of muscle insertion and calculated the loss of power arising from the fact that the muscle fibres are generally inserted in the tendon at an acute angle. [He later studied] the mechanics of walking, running and swimming, the position of the centre of gravity [and] its significance to ... the various movements" (Bastholm, 1950, p. 166).

Ponderal indices are ratios of weight to height and are intended to provide information on proportionate stoutness. More than half (eighteen of thirty-five) of the formulas of many investigators listed by Tucker and Lessa (1940) are, the present writer would conclude, entirely invalid, while many of the remainder are quite unsatisfactory in one or more respects. Only an index relating weight (or mass) to the cube of a linear dimension, such as height, can provide a valid ponderal index, as exemplified by the following:

$$(1) \frac{wt}{ht^3}$$

$$(2) \frac{ht}{\sqrt[3]{wt}}$$

It is, however, possible to derive a valid formula for a modified ponderal index by adjusting for the components of weight and height which tend to change least with variations in height -- those of the head and neck -- to relate somatic proportions with these portions excluded. In the near future, the writer plans to determine, empirically, of course, such formulas for adult males and females; they may approximate $wt/ht^{3.1}$. Different formulas, varying with age, will be needed for children undergoing growth. A markedly distinct type of formula should also be developed to show alterations in mean bodily proportions of adults and of children at varying ages, but such formulas will not only reflect variables like racial differences but also such transitory factors as culture.

In view of the foregoing information, it becomes evident that weight, mass, and volume vary almost precisely with the cube of any equivalent linear dimension for humans who are proportionately identical (geometrically similar). Likewise, strength varies with muscle tension, which in turn varies with the cross-sectional area, which is proportionate to the square of a dimension, such as height. So, theoretically at least -- and ignoring the minor complication in one of these of derivation from a

possibly preferable modified ponderal index -- the relationship of size to strength (f), when k is a constant, should conform to the following formulas:

$$(1) \quad f = k \cdot wt^{2/3}$$

$$(2) \quad \sqrt{f} = \sqrt{k} \cdot \sqrt[3]{wt}$$

$$(3) \quad f = k \cdot \frac{wt}{ht}$$

4. SELECTION OF POPULATION TO BE TESTED

Affecting human strength are the many variables previously listed, to which should be added that which has been ignored in strength studies to date -- genetic factors other than those associated with body-build. It might seem feasible to test the theoretical size-strength formula by comparing the square root of strength scores with the cube root of body-weight for the means or any other equivalent points on the distribution of scores of the general population divided into minute weight classes. But the number of subjects would need to be almost infinitely large, and the implicit assumption that no other strength determinant is correlated with weight is invalid, as exemplified by the association of greater weight with greater height but also with increased stoutness and adiposity.

An alternative is to select individuals with very high ratings for each determinant factor. But most of the factors are impossible to quantify at all precisely. Fortunately, the sport of weightlifting, with participants whose strength-testing performances manifest a degree of precise standardization of conditions rarely achieved in the laboratory, has recently spread to appreciable segments of the Western world's national societies. So it is possible to choose extremely deviant subjects from large populations, for the best weightlifters reveal by their performances that they rank very high (in or near the hundredth percentile) in all the component determinants, including health, previous nutrition, and motivation, as well as in such more readily observable factors as non-adiposity, exercise, and skill in the procedure tested.

Also, strength for a given body-weight in normal humans is affected by an upper limiting asymptote, a highly significant phenomenon apparently not recognized in earlier studies of human strength. So additional improvement beyond a high but frequently achieved level effects only rapidly diminishing returns in strength, which tends to reduce the variability of performance at the uppermost end of the strength-score distribution for a given body-weight. Furthermore, each environmental component, such as nutrition, exercise, and experience at weightlifting, is also affected by a comparably effective limiting asymptote, related to the general one. So the better the group of weightlifters, the more the asymptote will affect the performances, resulting in less variability of scores.

Consequently, there are two reasons -- uniformity of determinant factors other than size and the effect of limiting asymptotes -- both of which make it advisable to employ highly capable weightlifters as ideal subjects in any attempt to relate strength to size.

5. TESTS OF THEORETICAL SIZE-TO-STRENGTH FORMULA BY WEIGHTLIFTING SCORES

Since all the analyses in this section of the paper will be based upon weightlifting scores, it would be well to describe the performances at the outset. Seven lifts are recognized by the International Amateur Weight Lifting Federation: (1) two-hand military press, (2) two-hand snatch, (3) two-hand clean-and-jerk, (4) one-hand snatch with right arm, (5) one-hand snatch with left arm, (6) clean-and-jerk with right arm, and (7) clean-and-jerk with left arm. At least five additional lifts are occasionally used in competitions, but national and international (including Olympic) meets are normally restricted to the first three listed, with omission of the four one-hand lifts.

The two-hand military press is performed by grasping, palms down, the handle of the barbell, which is placed on the platform in front of the lifter. The bar is brought to the shoulders in a single movement while the lifter lowers his center of gravity, to aid the lift, by "splitting" or alternatively bending his legs. Then, in a second continuous motion, the arms are fully extended overhead, while legs and back remain almost motionless. In the two-hand snatch, the bar is placed, gripped, and raised vertically above the head with both arms and legs extended (at the termination of the lift) almost precisely as in the press, but all must be accomplished in a single movement. In the two-hand clean-and-jerk, the bar is first "cleaned" (brought to rest on the chest or fully-flexed arms) in essentially the same fashion as in the press, but the jerk consists of raising the bar overhead with the added advantage of flexing and then extending the legs while simultaneously extending the arms vertically. Hereafter in this paper, the three lifts will be designated simply "press," "snatch," and "jerk."

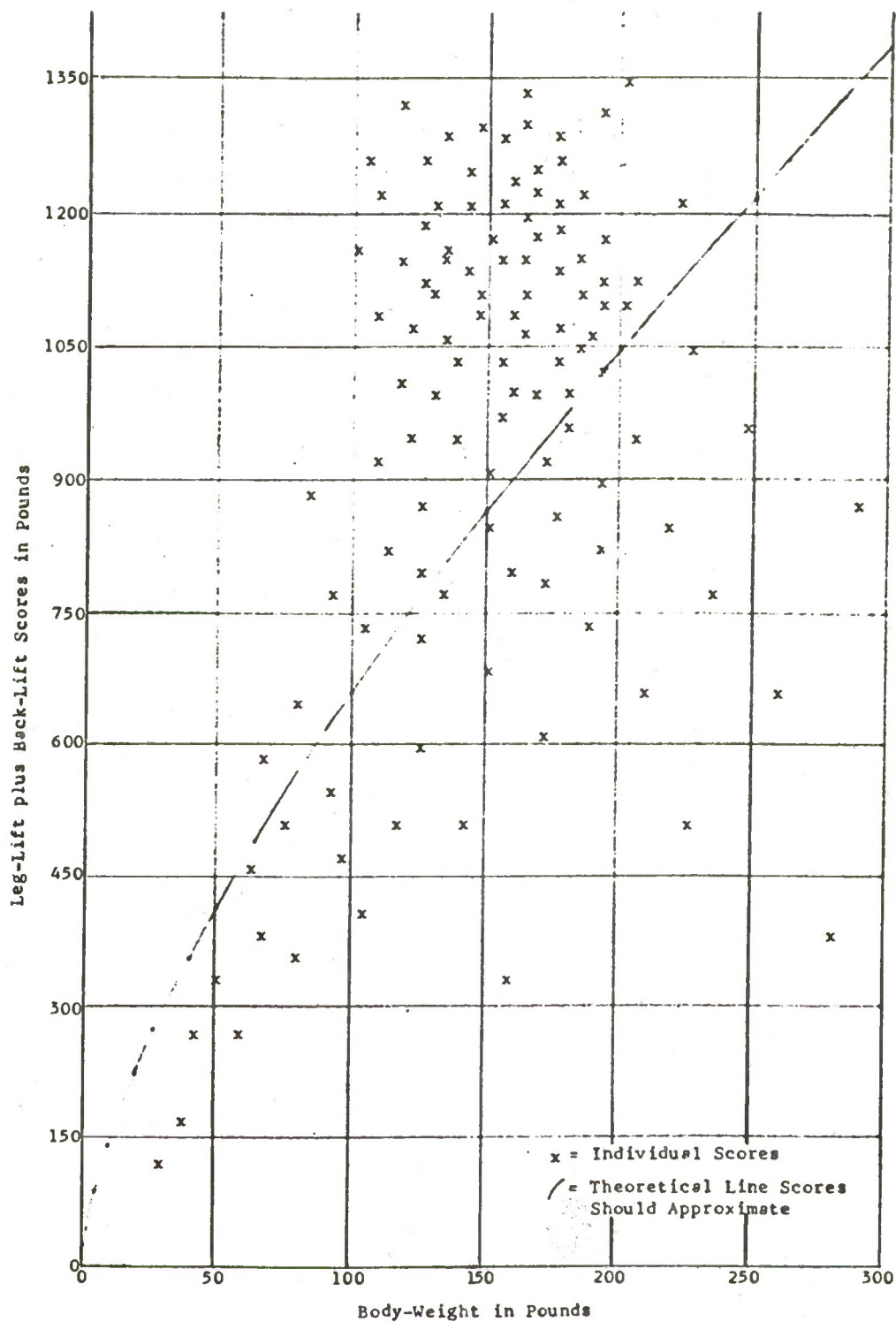
A minor source of difficulty to the following analysis is that some of the body-weight intervals have been altered at times during the past few decades. For example, the 112-pound and 118-pound body-weight classes, used by the American Athletic Union for a decade, were abandoned in 1939. The A.A.U. 128-pound class of 1929-1930 was then reduced to 126, and in 1940 to $123\frac{1}{2}$ (since this last change was performed to equate the European 56-kilogram class, it would more properly have been defined as 123.46 lb.). But most intervals have remained quite constant internationally for several decades. Bantamweights do not exceed 56 kg. ($123\frac{1}{2}$ lb.); featherweights, 60 kg. ($132\frac{1}{2}$ lb.); lightweights, 67.5 kg. ($148\frac{3}{4}$ lb.); middleweights, 75 kg. ($165\frac{3}{8}$ lb.); light-heavyweights, 82.5 kg. ($181\frac{7}{8}$ lb.); and heavyweights, in excess of 82.5 kg. In 1951, an additional middle-heavyweight class of 90 kg. ($198\frac{3}{8}$ lb.) was instituted in the United States; it has been employed in the 1952, 1956, and 1960 Olympiads, as well as in annual world meets.

To test the degree of congruence between the theoretical formula and empirical data, it must next be decided whether actual body-weight or the maximum permitted at the time of competitive weightlifting performance should be employed in calculations. First, it must be considered that the scores should represent as nearly equivalent points on the distribution curve of strength scores as possible; despite the limiting asymptote, attenuation at the uppermost end of the curve is sufficient to effect significant variation in the scores within the highest percentile. So if a champion lifter achieved the highest score despite an appreciable (and extremely unlikely) body-weight handicap, he would necessarily represent a far more extreme deviant than the champions in other weight classes who much more closely approached the maximum body-weight permitted. Therefore, it would be best to provide at least possible compensation for such an extreme deviant by calculating from the maximum weight permitted for scores in international, and perhaps national, competitions.

A closely associated question is whether to use weight^{2/3} or weight/height as the quantity which should be directly proportionate to strength (which should also be directly proportionate to cross-sectional muscle area). For reasons very similar to those in the preceding discussion, it seems almost as decidedly better to use weight^{2/3} for international championship scores. If, for example, an achondroplastic dwarf won an Olympic title, his advantageous shortness would quite surely be almost fully counterbalanced by the fact that, selected from a much smaller population (of dwarfs), he would almost certainly be not nearly so deviant as his winning counterparts in the other determinants. It would be well, however, to know stature (and less significantly the actual body-weight) in order to help identify the barely conceivable lifter combining extreme deviation in all generally applicable variables with exceptionally atypical body-build.

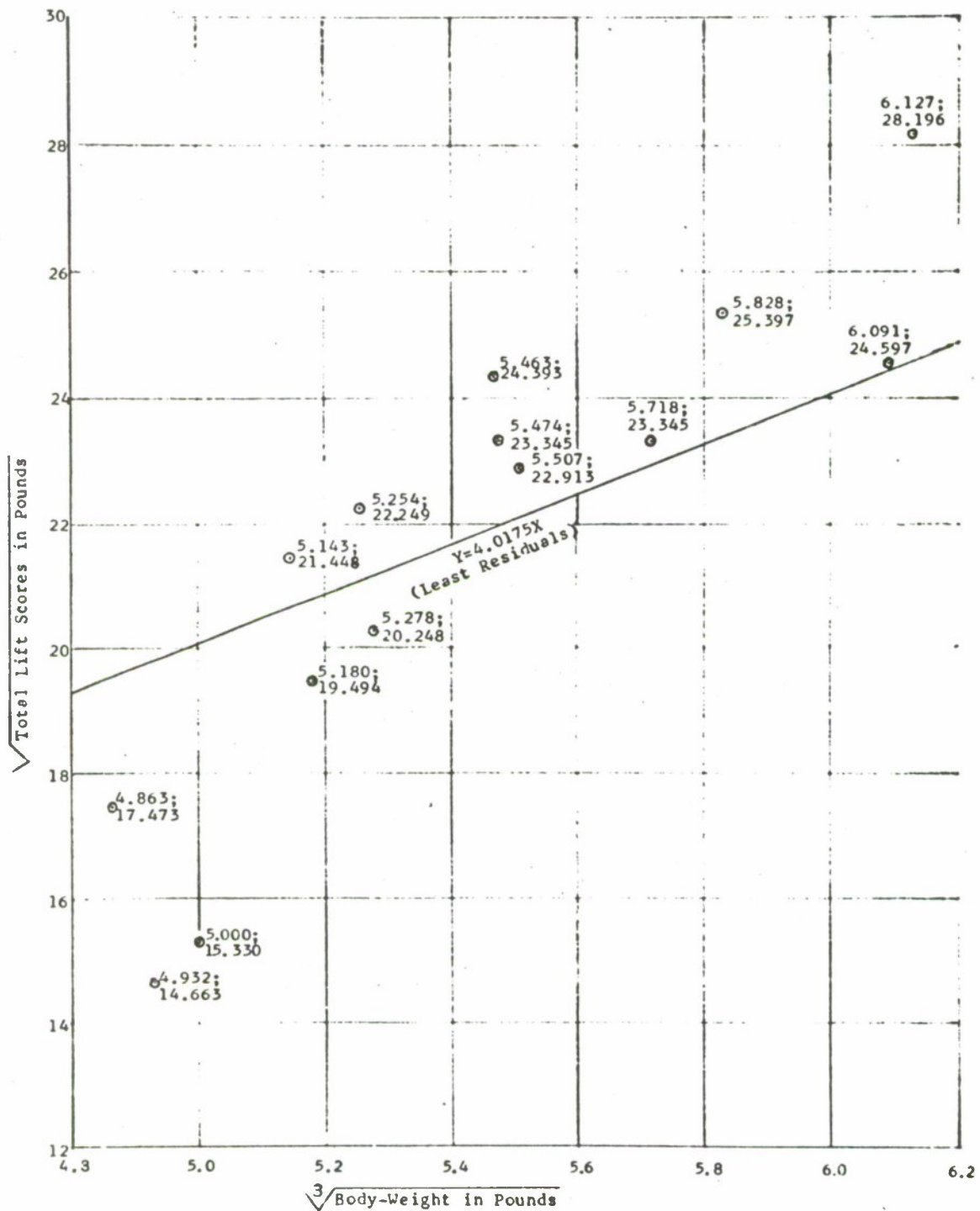
In Figure 1 is diagrammatically plotted the distribution of body-weight and leg-lift-plus-back-lift scores for a random population of American males. The curved line traversing the graph -- not a straight line as assumed by all previous students of this problem area -- represents the theoretical relationship of size to strength, based upon mean values for each minute body-weight class in the hypothetical population. In theory the actual size-strength examples might be expected to approximate this line closely. But the effect of the many variable determinants of strength other than body-size is so great that virtually nothing more can be observed than a tendency for larger individuals to be more frequently somewhat stronger, as well as a tendency for the lightest individuals to show below-line values (because of the higher incidence of immature subjects) and the heaviest to do likewise (because of the higher frequency of marked obesity).

Appreciable reduction of the variable factors is reflected in Figure 2, which represents the actual results for all entries of a weightlifting competition for novices. For greater facility in plotting scores and in calculating residuals, the exponential function curve was converted to a straight line by plotting the cube root of actual body-



Strength Scores and Body-Weight of a Random Population of American Males (Diagrammatic)

Figure 1



Total Scores of Pittsburgh Region Weightlifting
Competition for Novices, February 1, 1958

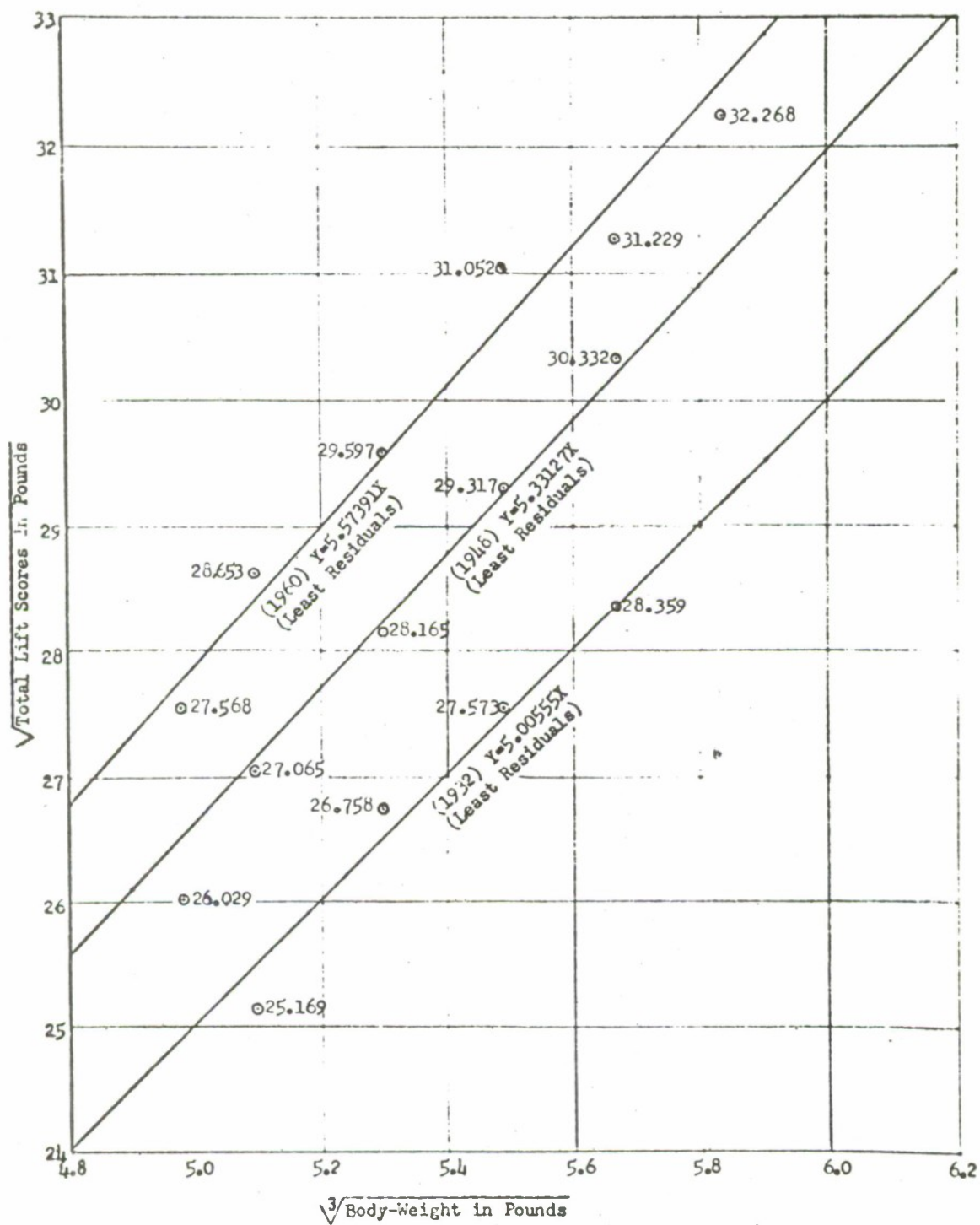
Figure 2

weight against the square root of strength scores, the total of the three standard lifts. As in all subsequent graphs, the theoretical line was plotted from mean values for body-weight and strength in the population analyzed; more precisely, it is the regression line passing through the origin -- as theory demands -- and resulting in the least total residuals ($Y - Y_1$). The greater clustering of plotted values about the line is evident, but the nature of this line is clearly deducible only theoretically.

Populations in which almost all of the component determinants of manifested strength are above the ninetieth percentile level (so the net percentile rating is in the uppermost small fraction of the hundredth percentile) are those of the 1932, 1948, and 1960 Olympic champions, whose performances are indicated in Figure 3, in which were employed maximum-permitted body-weight values of 123.500, 132.250, 148.750, 165.375, 181.875, and 198.375 lb. (with cube roots of 4.980, 5.095, 5.298, 5.489, 5.566, and 5.832, respectively). Because of effective selection from larger participant populations with better nutrition, increased training effort, and improved training methods -- as well as subtle psychological factors -- it would be anticipated that markedly higher scores would characterize successive Olympiads. This expected trend is not only simply illustrated in Figure 3, but also by a review of all Olympic Games, revealing only one case of a winning score not exceeding those of the same weight-class of all previous meets; this is strikingly illustrated by the fact that the winner of the first (1896) Olympics, had he been able forty years later to equal his performance as a youth, would nevertheless likely have failed to qualify for a U.S. Amateur Athletic Union certificate of successful completion of the novice phase.

Progressively greater conformance to theoretical expectation would also be anticipated, but the smallest residuals were found in 1948, when the standard error of prediction was only .09286 -- or, converted to lift-weights, 0.647 per cent -- and the average deviation from predicted scores was a mere 1 lb. 11 oz. for individual lifts, and this despite the fact that on the very day of the meet the weightlifters could scarcely have predicted their own performances within 17 lb. -- ten times as large a discrepancy. Considering the relatively great magnitude of score differences between and even within weight-classes, such precision of prediction seems remarkable indeed, and it should be emphasized that such precision of prediction is based upon the writer's theoretical formula, not upon an empirically established relationship.

Further analysis -- of the three highest scores for each weight-class in each of the three Olympiads -- demonstrates a consistent trend to greater conformity to prediction, as anticipated, when adjusted from absolute to relative values. Further computations reveal that even the minute deviations from the regression line follow consistently distinct patterns for each lift, and each deviation follows a pattern expectable on the basis of evident but very complex considerations. One of the slightly distorting factors is that of relative skeletal weight, which



Total Scores of 1932, 1948, and 1960 Olympic Champions

Figure 3

varies according to body-weight, proportion of muscle to adipose tissue, and relative stature (Edwards, 1960b). It is now possible, by the theoretical size-to-strength formula modified very slightly to allow for the other variables, to predict lifts even far more accurately than by the unmodified formula -- within ounces.

The final example to be considered in this paper is one drawn from the most precisely "controlled" populations of all, those of world weightlifting record-holders, who represent the most rigorous selection for all significant determinant factors. In Figure 4, current records for the press (Weightlifting, 1962, p. 32) are plotted. In this case, the regression line ($Y=3.20053X$ by least residuals) was calculated by the slightly more precise least-residuals-squared technique ($Y=3.198X$). The standard error of the square roots of the strength scores is only .0917, even though calculated from the less precise unmodified formula.

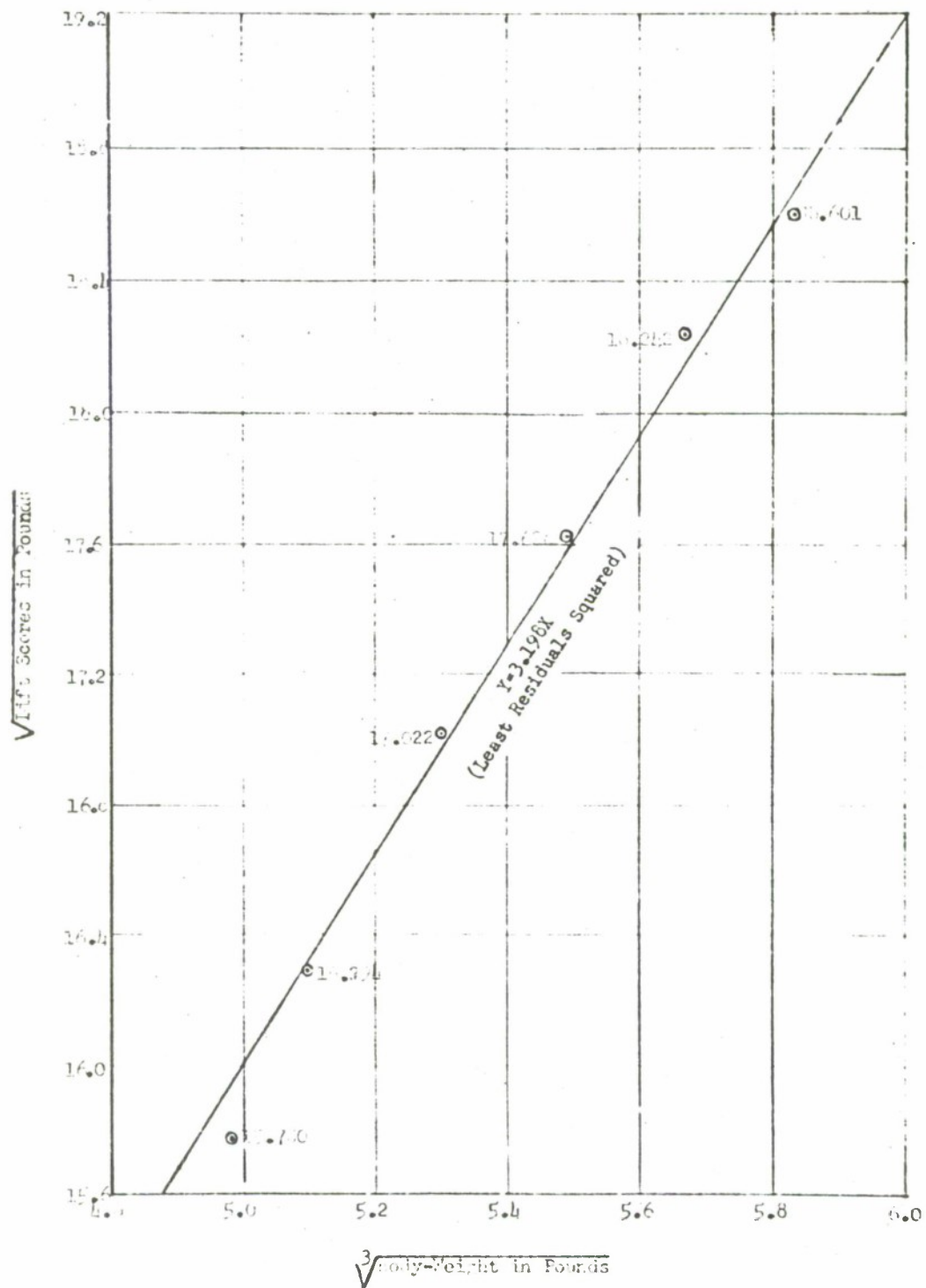
6. SUMMARY

Man has been most reluctant to consider himself objectively, but many scientists have nonetheless attempted to determine the effects of the many factors influencing strength, with most of them concentrating on the presumed mechanistic relationships of human strength to size. But inductive approaches -- theoretical formulations with subsequently attempted corroboration through empirical data -- have been as completely lacking in success as the much more frequent (and often very elaborately detailed) deductive approaches of the scores of investigators who have sought the solution to this problem.

The major difficulties in previous studies have concerned: (1) the essentiality of selecting a population of subjects for strength-testing in which all factors except size are virtually constant; (2) the fact that only those athletes with the best performance records, preferably on an international level, in a strength-indicating sport (weightlifting), thereby reveal near-equivalence in the other determinants of strength through high percentile ratings in each; (3) the fact that the strength-determining factors are asymptotically limited both individually and collectively; and (4) the theoretical relationships between size and strength, determined by principles of geometrical similitude.

The proper theoretical size-to-strength formula is that the square root of strength scores varies directly with the cube root of body-weight, or, a little more precisely (especially if height is slightly adjusted to allow for the smaller relative change in head-plus-neck proportionate height), with body-weight divided by height.

Comparisons with populations of progressively better weightlifters manifest proportionately improved conformance with theoretical predictions, as do successive Olympic scores. By the writer's simple cube root of maximum-permitted body-weight formula, world record lifts can be



1961 World Record Press Scores

Figure 4

predicted within a few pounds, despite their variability between different years and between the best weightlifters at any one time. But this remarkable conformance can actually be improved upon, for the minute deviations from the theoretical regression curve are regular and conform to understandable but highly complex distorting influences. The slightly modified theoretical formulas (different for each lift) can, even though the weightlifters have difficulty predicting their own performances within twenty pounds, predict record performances within ounces.

This study constitutes likely the most striking demonstration yet accomplished that even the more complex of man's physiological phenomena conform to universal laws and mechanistic principles.

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