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Evaluation of Maximal and Submaximal Static Muscle Exertions

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A model of the regulation of muscle strength exertion is proposed. Based on the model, methods are discussed to assess whether a subject exerts maximal or submaximal efforts. Results with 40 subjects indicate that a simple technique may be developed to judge if a subject is following instructions to exert a maximal contraction in a routine test of voluntary muscle strength.

INTRODUCTION

Assessment of human voluntary muscle strength is of considerable interest to the ergonomist. It describes human work capacity and, hence, is a basis for the design of work tasks and work equipment. However, routine measurement of static (isometric) muscle strength (such as that done by a plant physician) poses certain problems. For example, the tests cannot be intensive, due to danger of injury, or lengthy, due to time constraints. Also, subjects may not fully cooperate.

This paper describes a model of muscle strength regulation and related experiments. The results indicate a solution to problems encountered in routine testing of human isometric muscle strength, measured as force or torque applied by a subject to an external dynamometer.

STRENGTH REGULATION

Muscular strength is operationally described as a subject's capability for the exertion of force or torque to an external dynamometer over a specified period of time. (Separate definitions for static and dynamic muscular efforts have been developed previously; see Kroemer, 1970; 1978). This strength is the result of complicated internal functions, since it depends not only on the number of muscle fibers contracting and on the mechanical advantages prevailing, but also on internal activation and feedback control loops connecting the muscles involved with the central nervous system (Houk, 1979; Kroemer, 1979).

The muscle contraction effort is ultimately limited by the given structural (biomechanical) strength of the muscles, tendons, cartilage, bones, etc., in the body parts involved, taking into account such postural mechanical advantages as pull angles, lever arms about articulations, etc. Clearly, the true maximal

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TABLE 1

Factors Affecting Maximal Muscular Performance. (Kroemer, 1974)

	Likely Effect
Feedback of results	+
Instructions on how to exert strength	+
Arousal of ego involvement, aspiration	+
Pharmaceutical agents (drugs)	+
Startling noise, subject's outcry	+
Hypnosis	+
Setting of goals, incentives	+ or −
Competition, contest	+ or −
Verbal encouragement	+ or −
Spectators	?
Deception by researcher	?
Fear of injury	−
Deception by subject	−

+ = Increasing
− = Decreasing
? = Effect Unknown

strength capability usually cannot be tested in living human subjects. Ruptures of muscles or tendons, or of their attachments, are reported frequently from sports accidents; however, the circumstances cannot be well reconstructed experimentally and therefore do not provide a good source of information on muscle strength. Occasional feats of "super strength" are reported in anecdotal form, such as the proverbial mother lifting an automobile from her injured child. Again, no experimental setups seem feasible to simulate such a situation. Measurements taken on animals in vivo, or on human cadavers, provide only limited qualitative information on the human capacity to exert maximal muscle strength at work or in a physical test.

In routine test and work situations, a subject usually exerts a muscular output that is below the structural strength limit by a substantial safety margin. The technical term for this submaximal exertion is "maximal voluntary contraction" (MVC). Therefore, the result of any given strength test reflects that datum on a strength scale which the subject considers appropriate for exertion under the given conditions. Table 1 lists some of the circumstances that have been shown by various researchers to affect motivation of subjects, either raising or lowering the strength exertion score. However, these results are qualitative (see, for example, Hyvaerinen, Komi, and Puhakka, 1977; Kroemer, 1974a and b). There are no objective means to assess the motivation of subjects in routine strength tests that would allow the determination of the location of the actual strength datum on the scale of a subject's true voluntary contractile strength.

This brief discussion shows that, aside from skill and training (variables usually controlled in strength testing), a subject's muscle strength depends primarily on the voluntary activation of the muscles involved and the regulation of their contractions. Strength testing that is based on a suitable model of this control system should be more successful than previous empirical and nonstandardized approaches (Kroemer, 1978).

A MODEL OF MUSCLE STRENGTH CONTROL

Recent theoretical considerations and experimental findings (Astrand and Rodahl, 1977; Caldwell and Kroemer, 1977; Houk, 1979; Kroemer, 1970, 1974(a), 1977, 1978; Kroemer and Howard, 1970; Marras, 1978; Maton, 1976; Tesch and Karlsson, 1978; Thorstensson, Grimby, and Karlsson, 1976; and Viitasalo and Komi, 1978) have resulted in a proposed model of muscle strength control (Kroemer, 1979). Figure 1 depicts this closed-loop system, which links the cerebrum and cerebellum of the central nervous system (CNS) as controlling components, the feedforward signals as efferent components (E), motor units and associated muscle groups as regulated output components (MUSCLE), and feedback signals (F_1, F_2, F_3) as afferent

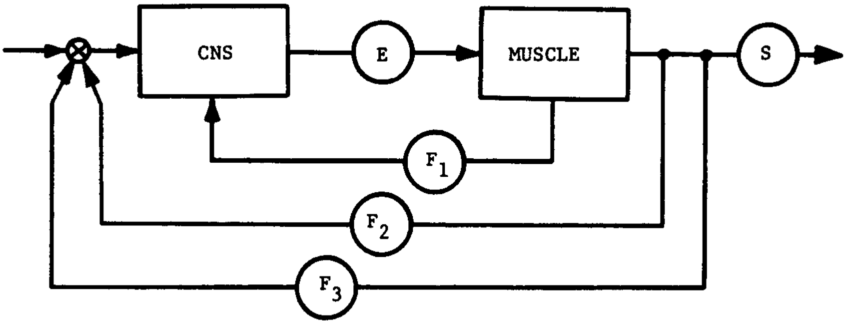

Figure 1. *Model of the Regulation of Muscle Strength Exertion* (*Kroemer, 1979*).

components. The system output is the muscle strength (S) measured with a dynamometer.

This model indicates that the system output depends on the intended strength output (S) which, in routine strength testing, is a function of the instructions given by the experimenter to the subject. Thus, depending on the intended muscle contractions, the CNS calls up a stereotypical mental "executive program" that may be innate or learned.

The executive program regulates nervous impulses transmitted along the efferent pathways (E), which can be observed and recorded via electromyograms (EMG). Major characteristics of these electrical activities are duration, amplitude, and frequency.

These signals excite certain types and numbers of muscle fibers and regulate their time profile of contraction. The muscle fibers involved may be F types (i.e., fast-twitch, high glycolytic) innervated by small motor neurons. Their concomitant F motor units generally are more anaerobic, more easily fatigued, and contract faster than the second group; S units are more aerobic, less easily fatigued, and contract more slowly.

For a submaximal (low tension) contraction, S motor units are primarily recruited. For increasing muscle tension, new motor units are recruited, and the neuron firing rate is increased. At higher levels of required strength, and for quick activation of muscles, F units, which have distinctly higher firing rates than the S units, are activated. Thus, one can distinguish between two major patterns of excitation coding: "recruitment coding" regulates the number of units; "rate coding" controls the frequency of firing of each unit. Minimal efforts can be achieved by recruiting just a few S units. Submaximal exertions require a complex mixture of rate and recruitment coding, while maximal exertions are primarily effected and maintained by rate coding.

Control of the muscular effort to generate the desired output profile requires feedback signals to the CNS for comparison of the existing state with the input program and for subsequent correction of the efferent impulses to achieve minimum difference between input and output. The feedback subsystem may be divided into three loops: "primary loops" (F_1) originate at the Golgi and spindle organs of the muscles directly participating in the generation of strength output. "Secondary loops" (F_2) originate at muscles that stiffen the body, at Ruffini organs, and at surface sensors responding to pressure changes, such as at the hand applying force to the dynamometer or at body support surfaces. "External loops" (F_3) include primarily visual and acoustic feedback, such as seeing a pointer move or hearing sounds representing the strength (S) exerted at the dynamometer.

PRACTICAL ASSESSMENT METHODS

The model just described can be used in a systematic consideration of the possible approaches to measuring static maximal voluntary contractions (MVC) exhibited by a subject in a routine testing situation.

The "executive program" of the CNS depends on the time-strength profile of the intended muscle contraction which, in turn, depends on the test regimen employed. In the past, many very different strength outputs have been requested from test subjects, such as slow or sudden force increases, jerks (impulse or peak forces generated over very short time periods), single or quickly repeated efforts, smooth exertions sustained over a period of time, etc. In fact, some contradictory strength results reported in the literature may be more indicative of differences in experimental procedure than of differences in muscle strength of the subjects (Kroemer, 1975). A few years ago, finally, one standardized test procedure (the "Caldwell Regimen") was developed for isometric tests (Caldwell, Chaffin, Dukes-Dobos, Kroemer, Laubach, Snook, and Wasserman, 1974; also reported by Chaffin, 1975). It is schematically shown in Figure 2. After a buildup time of about 2 s, the subject is required to maintain a steady maximal exertion for at least 3 s. This (average) level is taken as the subject's strength score.

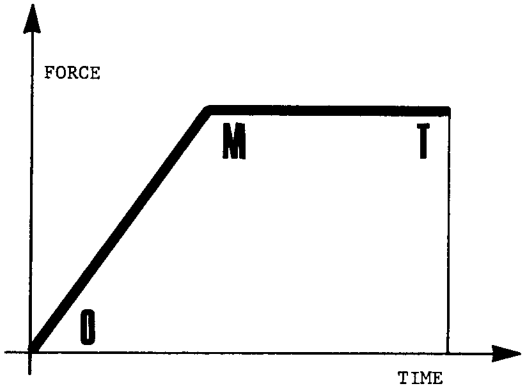

Figure 2. *Schematic Depiction of the Strength Output Requested in the Caldwell Regimen. After the buildup phase (O to M), the maximal level is held for at least 3 seconds (M to T).*

The Caldwell Regimen has solved many practical testing problems. Still, it obviously does not control for the mental *executive program,* which includes the willingness of the subject to cooperate. The mental program is not accessible, or measureable, with current techniques for routine testing.

The signals along the *efferent paths* of the nervous system (E) determine the excitation of motor units. Duration, frequency, and amplitude of the myoelectric activity can be monitored with needle or surface electrodes. Standard procedures exist for recording, filtering, and analyzing EMGs.

With current EMG technology, only a few problems still exist for routine testing: to capture the signals to the truly limiting motor units (possibly small or remote muscles); to identify the relationship between excitation signals and strength output of the affected biomechanical unit (depending on muscles, bones, joints, pull angles, etc); to avoid the partial disrobing of the subject; and to simplify the relatively complex sensing, monitoring, recording, and analyzing equipment. Thus, despite their promising nature, EMG methods have not yet been developed into single routine measurement techniques.

The number and type of muscles directly involved determine the strength output. For some simple biomechanical units (e.g., the elbow system) one knows the number of muscles involved. If more complex body subsystems are included in the effort, the number and relative contribution of muscle groups are not easily described. Furthermore, muscle mass is not readily measured, and the contractile strength of bundled muscle fibers per cross section ranges from 35 to 60 Ncm^{-2}. The different fiber types (e.g., fast and slow twitch) must be determined by biopsy.

The mechanical advantages (pull angles, leverarms, etc.) at which a given muscle acts are, in fact, not a confounding factor in static (isometric) strength exertions. Even through difficult to determine, they are considered constant in such tests, and therefore do not enter static biomechanical models as variables. (However, they become highly important variables in dynamic strength testing.)

Obviously, the routine assessment of muscular characteristics by anthropometry, biochemistry, or biomechanics is not sufficiently developed to predict the strength output.

As a possible alternative, the *afferent feedback* system provides a variety of measurement opportunities. However, the "primary loops" (F_1) originating at the Golgi and spindle organs of the muscles directly involved, are anatomically difficult to locate, and technically difficult to monitor. Basically the same problem exists with respect to the "secondary loops" (F_2) originating at muscles and joints that stiffen and support the body, or at tactile skin sensors that respond to pressure changes at the body support surfaces. The monitoring problem is confounded by the large number of sensors and their wide distribution over various body parts.

The elaborate excitation and feedback systems for the control of muscular contractions can be tapped, in theory, at different control loops. However, due to the large variety of possible loops, the difficulty of predicting if and when these loops will be activated, the large amount of noise existing in the system, and the difficulty of relating occurrence, frequencies, and amplitudes of observed signals to the intensity and duration of specific muscular contractions, serious practical problems exist.

The "external loops" (F_3) include predominantly visual feedback (seeing an instrument indicating the strength exerted) and acoustical feedback (hearing sounds representing the force output, or the experimenter's voice). Such feedback affects the internal excitation program directly and changes the strength output. In fact, this feedback can be used easily by the experimenter to manipulate the strength exertion. (Many reports on strength tests fail to mention the controls exercised over the external feedback.)

In conclusion, analysis of the feed-forward (E) and feedback signals (F_1,F_2) appears to be the most promising way to indicate whether or not a subject exerts an MVC or only a submaximal effort in a strength test. However, the currently available techniques require experimental procedures that are too demanding for routine testing. Fortunately, a synthetic approach based on the model is feasible (Kroemer and Marras, 1980a). The procedure uses the total system output (S) as its own control in repeated tests.

While this approach does not attempt to measure the internal functions involved, it relies on the assumption that excitation, activation, and control of voluntary muscle strength exertion are performed according to the model presented. Specifically, it is presumed that submaximal efforts require a complex mixture of rate and recruitment code excitation, necessitating frequent and repeated CNS input adjustments according to the feedback describing the momentary output. Thus, submaximal force development should be difficult to regulate, particularly if accompanied by restricted external feedback. In contrast, a maximal contraction is simply achieved by an all-out use of recruitment and rate coding, with the feedback indicating only that full effort.

In a testing situation designed to interfere with the feedback system (in a routine test easily done by cutting off the external feedback loop F_3, while employing the highly standardized Caldwell Regimen) one would expect strength buildup to an aspired submaximal level to require much information processing and contraction regulation, hence to take a relatively long time; in comparison, a maximal effort should be achieved quickly. Such a result would not only support the theoretical model, but would also offer practical means to assess whether a subject exerts a submaximal or maximal muscular contraction.

According to the preceding considerations, two hypotheses can be formulated:

(1) Maximal voluntary muscle contractions are effected by full use of both recruitment and rate coding, and need little external feedback control during the buildup phase. Thus, MVCs need relatively little time per strength unit for buildup to the maximal level.

(2) Submaximal exertions are regulated by composite rate and recruitment coding and require complex feedback to achieve intended levels of strength output. Thus, a relatively long time is needed per strength unit for buildup to the intended submaximal contraction level.

EXPERIMENTAL METHOD

Experiments were designed and performed to test the experimental hypotheses in the following isometric efforts: elbow flexion, finger flexion, knee flexion, and knee extension. These experiments extended previously reported tests (Kroemer and Marras, 1980a), in which 30 subjects performed elbow flexions only. The current experiments also considered two indices: peak force level and maintained force level recorded. (For more details see Kroemer and Marras, 1980b.)

Subjects

Twenty female and 20 male undergraduates from the Wayne State University volunteered their participation for payment of a fixed fee. While no specific selection criteria were applied, no persons obviously unable to perform muscular contractions volunteered. Key descriptors of the subjects are the following: female (male), averages: age 22.5 (22.8) years; stature 163.7 (176.3) cm; weight 57.3 (76.5) kg; lever forearm (elbow-cuff) 24.9 (28.5) cm; lever lower leg (knee-cuff) 37.1 (38.3) cm.

Experimental Design

Every subject served as his or her own control. The subjects were asked to produce 100%, 75%, 50%, and 25% of their individual maximal strength in elbow, finger, and knee flexion, and knee extension. Four tests were performed for each condition. The trial orders were counterbalanced to control for carry-over effects and were arranged to alternate between arm, finger, and leg exertions. The subjects did not receive any feedback about their performance until completion of all tests.

Apparatus

A special experimental "chair" was used, which had a flat, horizontal seat pan (38 cm by 56 cm), and a vertical straight back (66 cm by 56 cm). On the right side was a rigid horizontal armrest, which extended forward 23 cm from the backrest. Its height could be varied between 20 and 30 cm above the seat. With the elbow angle about 90 degrees, the subject propped the elbow of the right arm on the rest and extended the forearm directly forward. A nonelastic cuff was placed around the wrist and was connected rigidly to a load cell directly underneath.

A similar arrangement was used for the knee strength tests. With the thigh resting on the seat pan, the lower leg hung down, with no foot support provided. Thus, the knee angle was approximately 90 degrees. A leg cuff was put slightly above the ankle of the right foot. The cuff was connected horizontally with a load cell recording either extension or flexion force.

For the finger flexion exertions, the subject put the right hand palm flat on a horizontal surface, which was slightly above elbow height. The extended right forefinger was placed on a dynamometer so that the tip of

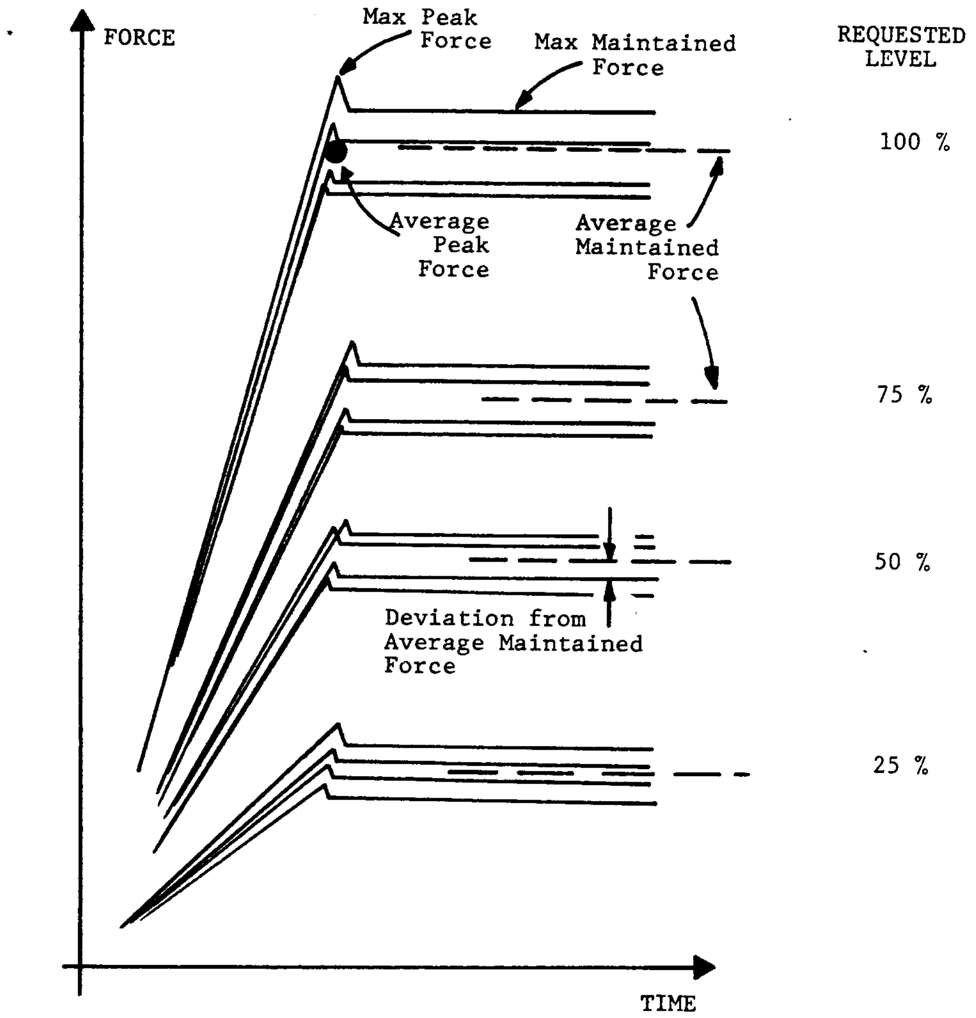

Figure 3. *Bases for Statistical Treatment of the Experimental Data (Schematically).*

the finger extended 1 cm onto its flat surface.

The outputs of the load cells were recorded in analog form.

Procedure

The countdown for each trial was as follows, in one second intervals: "-3, -2, -1, start, 1, 2, 3, 4, 5, stop." No attempt was made to control the length of the force buildup, except that it was understood that the subject would begin to contract upon the word "start" and achieve the level of force requested no later than at about the word "2." (Thus, the standard Caldwell Regimen for static strength testing was employed.) A test score was accepted if the force recorded during the maintained level phase did not vary by more than +10% of its average.

Analysis

Since each subject was asked to exert force at four different levels, and three repetitions were performed at each of these levels, four different analog recordings per subject and type of exertion were obtained at each level. They are shown schematically in Figure 3.

First, the onset slopes were read. For this the increase line (generally found to be straight through most of the buildup phase) was extended to pass through the zero and maintained force levels (O-M in Figure 2). Then, the average maintained force was read from the strip chart (Line M-T in Figure 2). Finally, the maximal peak force during the exertion was read.

For each subject, and separately for the maintained level forces and the peak forces, the average of the four trials for the 100% efforts was calculated. These averages served as "bases" for normalization of the data, in which each recorded force was converted into percent of the subject's base. Thus, the absolute forces reflecting each subject's individual strength could be used in percent form as inputs to ANOVAs.

Also, for each trial and subject, the correlation coefficients between onset slope and attained maximal force (normalized level or peak values) were computed.

All significance tests (*F* or *t*, as appropriate)

TABLE 2

Exerted Forces (N) Read as Peak and Level Values at Four Requested Strength Portions of MVC

		100% MVC			*75% MVC*			*50% MVC*			*25% MVC*		
		MEAN	*S*	*CV*	*MEAN*	*S*	*CV*	*MEAN*	*S*	*CV*	*MEAN*	*S*	*CV*
KNEE FLEXION													
20 Female Subjects	Peak	103.3	40.9	0.40	70.7	30.3	0.43	56.0	25.8	0.46	39.3	19.0	0.48
	Level	100.3	39.5	0.39	66.5	29.3	0.43	54.0	25.6	0.47	38.0	18.7	0.49
20 Male Subjects	Peak	191.4	60.7	0.32	122.9	56.3	0.46	98.7	50.4	0.51	68.8	36.8	0.54
	Level	185.3	59.8	0.32	119.3	55.3	0.46	96.3	49.4	0.51	67.1	36.6	0.54
All Subjects	Peak	147.4	67.9	0.46	96.8	52.2	0.54	77.3	45.3	0.59	54.0	32.8	0.61
	Level	142.8	66.2	0.46	93.9	51.1	0.54	75.1	44.7	0.59	52.5	32.5	0.62
KNEE EXTENSION													
Female Subjects	Peak	150.8	63.1	0.42	92.0	42.1	0.46	68.8	36.1	0.52	47.5	26.4	0.55
	Level	144.9	60.7	0.42	88.2	41.1	0.47	65.6	35.3	0.54	45.0	25.0	0.58
Male Subjects	Peak	274.0	91.4	0.33	159.6	57.9	0.36	119.9	48.4	0.40	82.4	40.5	0.49
	Level	263.5	86.0	0.34	153.6	56.7	0.37	114.8	47.5	0.41	78.3	39.2	0.50
All Subjects	Peak	212.4	99.8	0.47	125.8	60.9	0.48	94.3	49.7	0.53	64.9	38.4	0.59
	Level	204.2	96.4	0.47	120.9	59.3	0.49	90.2	48.6	0.54	61.6	37.2	0.60
FINGER FLEXION													
Female Subjects	Peak	23.1	7.0	0.30	11.6	5.7	0.49	8.1	4.3	0.52	4.4	3.0	0.68
	Level	19.4	6.6	0.34	9.3	4.5	0.48	6.4	3.2	0.50	3.2	2.0	0.63
Male Subjects	Peak	43.3	15.5	0.36	26.0	14.5	0.56	20.0	12.5	0.63	12.0	9.8	0.82
	Level	37.4	14.7	0.39	20.5	11.9	0.58	15.3	9.8	0.64	9.6	7.8	0.82
All Subjects	Peak	33.2	15.5	0.47	18.8	13.2	0.70	14.1	11.1	0.79	8.2	8.2	1.00
	Level	28.4	14.5	0.51	14.9	10.6	0.71	10.8	8.5	0.79	6.4	6.5	1.02
ELBOW FLEXION													
Female Subjects	Peak	161.7	44.8	0.28	97.1	38.6	0.40	75.6	35.8	0.47	47.4	21.6	0.46
	Level	140.9	45.1	0.32	75.3	31.6	0.42	57.9	29.9	0.52	39.7	18.0	0.51
Male Subjects	Peak	363.3	82.7	0.23	211.5	80.9	0.38	156.6	62.4	0.40	100.4	45.5	0.45
	Level	335.2	80.1	0.24	167.0	70.2	0.42	121.6	52.3	0.43	80.1	39.5	0.49
All Subjects	Peak	262.5	120.8	0.46	152.1	85.3	0.55	116.1	65.0	0.56	73.9	44.4	0.60
	Level	238.0	117.0	0.49	121.1	71.2	0.59	89.7	53.2	0.59	57.9	37.9	0.66

TABLE 3

Actually Exerted Percentages at Four Requested Strength Portions of MVC. Average values of all 40 subjects

		*100% MVC**	*75% MVC*	*50% MVC*	*25% MVC*
Knee Flexion	Peak	100	65.3	51.6	36.9
	Level	100	65.2	51.5	36.9
Knee Extension	Peak	100	60.3	44.5	30.6
	Level	100	60.1	44.0	30.1
Finger Flexion	Peak	100	53.7	39.5	22.6
	Level	100	50.4	36.2	20.8
Elbow Flexion	Peak	100	58.0	44.2	28.2
	Level	100	50.8	38.1	24.3

* by definition

were performed with an error probability of $p \leq 0.01$.

RESULTS

Tables 2 through 5 present the results of the experiments and of the statistical analysis.

The forces recorded as either peak or level values (in newtons) are listed in Table 2. Separately for female and male subjects, means and coefficients of variation are given for the four reported strength portions of the individual MVCs; Table 3 shows the actual exerted percentages, when the subjects were asked to apply either full MVC (100%, by definition) or 75%, 50%, or 25% thereof; Table 4 describes how much force (in newtons) was developed per time unit (second) at the four portions of individual strength; and Table 5 contains the correlation coefficients calculated between the speed of force buildup, and the actually attained portion of MVC.

Table 2 indicates that the forces exerted by

TABLE 4

Onset Slopes (Ns^{-1}) at Four Requested Strength Portions of MVC

	100% MVC		*75% MVC*		*50% MVC*		*25% MVC*	
Subjects	*Mean*	*S*	*Mean*	*S*	*Mean*	*S*	*Mean*	*S*
	KNEE FLEXION							
20 Female	165.77	112.93	108.48	64.58	80.91	46.04	61.03	32.83
20 Male	662.87	582.27	281.37	240.99	190.73	174.36	128.50	86.20
All	414.32	487.53	194.95	196.46	135.84	138.82	94.78	73.43
	KNEE EXTENSION							
15 Female	222.93	96.34	177.52	171.96	120.58	72.50	97.59	46.53
15 Male	946.82	689.42	407.38	356.94	328.03	319.94	190.50	137.44
All	584.90	610.96	292.45	302.81	224.31	254.06	144.07	112.62
	FINGER FLEXION							
Female	64.67	32.16	26.24	17.17	21.22	13.61	11.61	9.87
Male	154.39	116.76	82.33	74.59	72.86	79.31	36.47	31.49
All	109.51	96.70	54.26	60.94	47.06	62.45	24.02	26.42
	ELBOW FLEXION							
Female	381.10	212.88	188.01	81.57	175.91	112.35	105.73	52.57
Male	1,216.37	621.28	564.75	351.87	367.57	231.78	228.80	137.40
All	798.71	624.57	376.38	317.36	271.77	205.80	167.29	120.85

TABLE 5

Correlation Coefficients Between Onset Slope and Achieved Exertion

	Knee Flexion	*Knee Extension*	*Finger Flexion*	*Elbow Flexion*
Peak Based	0.790	0.785	0.860	0.870
Based on Maintained Level	0.790	0.810	0.835	0.850

the male subjects are considerably larger than those exhibited by the female subjects. The range of forces are similar to the ranges found in an earlier study with 30 subjects (Kroemer and Marras, 1980a). The peak forces are naturally numerically larger than the level forces, but the differences are not statistically significant. The standard deviations decrease with diminishing force levels. This is made obvious by the coefficients of variation (standard deviation divided by the associated mean). Despite the remarkably monotonic trend, the variability differences among force levels were not statistically significant.

Table 3 shows that the subjects found it rather difficult to exert the requested force levels without the benefit of feedback about the actually exerted forces. These findings are similar to the results of the previous study.

Tables 4 and 5 summarize the findings related to the experimental hypothesis. As Table 4 shows, both the female and the male subjects exhibited the flattest onset slopes for the lowest required exertions and increasingly steeper force buildups with increased required forces. The 100% level request, i.e., the instruction to exert the maximum voluntary contraction, brought about the fastest force-per-time strength development.

The correlation coefficients between onset slope and the actual exertion in Table 5 are all positive, high, and significant ($p \leq 0.01$). This, again, indicates the relationship between strength buildup and the aspired strength level.

This relationship between intended level of exertion and the contraction/time development is consistently exhibited with all four kinds of strength exertions, despite the disparities in biomechanical features of the included body segments and their distinct uses: knee extensions and flexions are rather powerful and are used predominantly for gross strength outputs. The elbow also represents a biomechanically rather simple system, with elbow flexions being reasonably strong but also often used for rather finely controlled motions. The finger represents a biomechanically much more complex system and yields rather small force outputs.

DISCUSSION

In an earlier study, 30 subjects were tested in elbow flexion alone (Kroemer and Marras, 1980a). Here, 40 subjects were tested in elbow, finger, and knee flexion, and in knee extension. Regarding elbow flexion, the two test results are virtually the same. Both studies support the experimental hypotheses.

Incidentally, both studies refute the long-held assumption that, via repeated testing, one could distinguish submaximal exertions from MVCs simply by the variability of the test results, with more variability at lower strength portions. While there was a monotonical trend in the coefficients of variations in that direction, the standard deviations showed a trend running in the direction opposite to the classic belief. In any case, the differences in variability were not statistically significant.

The findings of this study (and of the earlier one) can be summarized as follows:

(1) The ratio between strength of muscle contraction and the time needed for its buildup appears related to the magnitude of the strength exertion. This finding supports the experimental hypotheses, and thus the model assumption that submaximal strength outputs require more complex nervous control than do maximum exertions. This points to an interesting practical application: the onset slope of a muscle strength exertion recorded at an external dynamometer could be used to indicate whether or not a subject follows the instruction to perform a maximal isometric muscle strength exertion, and possibly to indicate what actual level of individual strength capability is being exhibited.

(2 Whether peak strength data or level strength data are analyzed, the same interpretations of the results regarding strength information are obtained, provided that the Caldwell Regimen is used.

(3) The variability of strength data recorded in repeated tests is not a suitable indicator for the magnitude of the subject's effort.

These results are a source of optimism in the continuing effort to standardize and simplify the methodology for determining human physical strength characteristics.

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