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Towards an Objective Assessment of the "Maximal Voluntary Contraction" Component in Routine Muscle Strength Measurements

K. H. E. Kroemer and William S. Marras

Ergonomics Research Laboratory, Department of Industrial Engineering and Operations Research, Wayne State University, Detroit, MI 48202, USA

Summary. Routine measurements of muscle strength capabilities commonly use external dynamometers against which the subject exerts maximal voluntary contractions of muscles in static (isometric) tests. These tests require active cooperation of the subject, i.e., full motivation to "give the best". At present, no practicable techniques exist that provide objective clues indicating that indeed a maximal effort is delivered, or if only a portion of the available strength is exerted. This paper describes experiments performed with 30 subjects which indicate that the rate of strength build-up in repeated exertions may provide objective criteria to judge whether or not a subject exerts full muscular strength in a routine test.

Key words: Routine muscle strength testing – Maximal vs. submaximal efforts

The routine assessment of human maximal muscle strength has always been of practical importance and a difficult problem. The testing is critical because the results are either used to design the work or equipment so that it meets the operator's capabilities, or to select suitable personnel. The measurement is difficult because, in routine testing, subjects are usually naive, available only for short time periods, cannot be subjected to extensive testing or training, and may or may not fully cooperate. While, in fact, most of our everyday muscular activities are performed dynamically, i.e., body masses are moved and muscle lengths change, almost all strength testing is done on the much simpler isometric or static exertion, with no overt body movement.

In this context, "routine testing" implies several or all of the following contraints:

Subjects: Available only for short periods of time; many to be tested; possibly not used to physical exertions; not familiar with testing situation; may or may not collaborate in exerting a maximal effort.

Offprint requests to: Dr. K. H. E. Kroemer (address see above)

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Instrumentation: Use of simple dynamometer; time-history of exerted force or torque recorded.

Test Condition: No invasive techniques; no disrobing of subject; simple strength data recording and evaluation; test administered by one person.

Research was performed to develop a method for routine testing of isometric muscle strength, measured as the force applied to an external dynamometer, which indicates if the subject fully cooperates in applying a maximal effort.

Experimental Hypotheses

Muscular strength has been operationally defined as a subject's capability for the exertion of force or torque to an external dynamometer over a specified period of time (Kroemer 1970, 1978). The strength score exerted is the result of complex interactions of internal functions which depend not only on the number of muscle fibers involved and on the mechanical advantages (body and segment positions) prevailing, but also on activation and feedback control among the muscles involved and the central nervous system (Houk 1979; Kroemer 1979; Kroemer and Marras 1980).

The contraction effort is ultimately limited by the given structural (biomechanical) properties of muscles, tendons, cartilage, bones, etc., of the body parts involved. In a routine test situation, even a cooperative subject exerts a strength score that is by some (unknown) safety margin below the structural strength limit. This fractional strength exertion is indicated by the technical term "maximal voluntary contraction, MVC". Table 1 lists some of the circumstances that have been shown to affect performances of subjects, either positively, negatively, or in an unpredictable manner. These findings are qualitative (Kroemer 1977; Hyvareinen et al. 1977), and objective means to assess the

Table 1. Factors affecting motivation and increasing (+) or decreasing (−) 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	−

motivation in routine strength tests are not at hand which would allow the determination of the location of the actual strength datum on the scale of the subject's true muscle strength.

Beck and Hettinger (1956) and Rohmert and Sieber (1960) pointed out some of the difficulties involved in trying to assess whether or not the subject truly exerted a MVC, or if a submaximal exertion was purposely presented as a maximal one. They suggested that a subject faking maximal exertions shows more variability in repeated tests than a person truly presenting MVCs. Such telltale would be useful not only for cases of occupational injuries that allegedly reduced muscular capabilities, but could play a critical role in routine strength testing.

It appears that every researcher has a special technique supposedly provoking maximal cooperation (motivation) of a subject. In fact, after comparing strength test results performed on seemingly similar subject groups it has been suspected that differences in the reported results might be more indicative of different testing techniques than of true differences in the muscle strength capabilities of the subject groups (Kroemer 1970, 1975). Only recently one standardized test regimen has been widely accepted for isometric strength measurements (Caldwell et al. 1974). After a build-up phase of no more than 2 s, the subject is required to maintain a steady maximal exertion for at least 3 s. This maintained strength level provides the datum (average) describing the subject's score. Figure 1 shows schematically the required strength exertion over time. The standard regimen also includes a controlled approach to achieve the subject's cooperation. However, even this carefully designed and well-tested regimen controls a subject's cooperation only qualitatively.

Based primarily on the compendium by Astrand and Rodahl (1977), a model has been developed (Kroemer 1979) that assumes a stereotypical mental "executive program" which regulates the muscular contraction according to the intended strength output profile (such as required by the Caldwell regimen). This executive program, originating at the cerebral or cerebellar portions of the central nervous system (CNS), regulates the activation impulses transmitted along the efferent pathways to the motor units. Here they excite certain types and numbers of muscle fibers, and by regulating the sequence and speed of

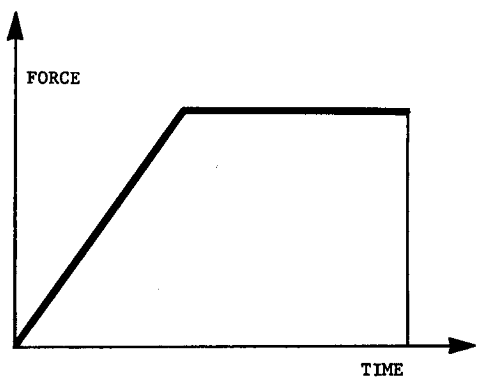

Fig. 1. Standard exertion program. The subject increases the contraction strength to a maximal value within about 2 s, and maintains this level for 3–4 s (Caldwell et al. 1974)

contraction determine the strength exerted at the dynamometer. For a submaximal (low tension) muscular contraction, primarily slowly contracting S motor units are recruited, with new motor units added with increasing muscle tension. For even higher levels of required strength, and for quick activation of muscle groups, F units are activated in addition. The F units have distinctly higher firing rates than the S units, as shown in the EMG. Thus, one can distinguish between two major patterns of activation coding. "Recruitment coding" regulates the number of types of units involved. "Rate coding" controls the frequency of firing. (Other codes may also be present, see Maton 1976).

Regulation of the muscular effort, to generate the desired output profile at the dynamometer, requires extensive feedback signals along the afferent pathways to the CNS for comparison of the existing contraction state with the executive program, and for corrections of the efferent impulses to achieve minimum differences between input and output.

This model suggests that submaximal muscle strength exertions usually require a mixture of rate and recruitment coding, associated with a complex feedback pattern of signals. This would require a relatively lengthy build-up phase until an intended submaximal level force is obtained according to the Caldwell regimen (hypothesis no. 1). In contrast, a maximal exertion fully uses both recruitment and rate coding as efferent activation signals, with afferent feedback signals simply indicating this full use. Thus, a MVC would be achieved rather quickly (hypothesis no. 2).

Whereas these hypotheses relate to the build-up phase of strength exertion, earlier suggestions by Beck and Hettinger (1956) and Rohmert and Sieber (1960) refer to the maintained phase of strength exertion. These researchers postulated more variability of the strength scores in submaximal efforts than in MVC's (hypothesis no. 3).

Experiments were performed to test these three experimental hypotheses.

Experimental Method

The experiments were performed in two stages. First, pilot studies were conducted with 12 subjects, followed by the main study with 30 subjects. In each case, elbow flexion exertions were required, with the subjects seated in a rigid chair that provided support to both the back and to the arm used. An arm rest supported the right elbow, with the forearm horizontal and the upper arm vertical. The subject exerted an attempted (isometric) elbow flexion, with a wrist strap connected to a load cell transmitting the exerted torque. The scores were recorded in analog form on a strip chart recorder, read off by the experimenter and subjected to appropriate statistical analyses, such as ANOVA, F-test, and t-test.

The experimental procedure followed the standard Caldwell regimen. In essence, this requires the subject to increase the muscle tension smoothly to the desired level within about 2 s, and to maintain this level for at least 3 s. The average value of these 3 s is calculated and accepted as the strength score, provided the actual exertion during that time period did not vary by more than $\pm 10\%$ of the average value. In addition to the average level forces, also the onset slopes of the force build-up were read from the records and expressed in terms of force units per second.

Table 2. Onset slopes (in Ns^{-1}) to reach the four requested strength levels

Subjects	25% Level				50% Level				75% Level				100% Level			
	Mean		S.D.		Mean		S.D.		Mean		S.D.		Mean		S.D.	
	$\bar{X}_5$	$\bar{X}_{10}$	S_5	S_{10}	$\bar{X}_5$	$\bar{X}_{10}$	S_5	S_{10}	$\bar{X}_5$	$\bar{X}_{10}$	S_5	S_{10}	$\bar{X}_5$	$\bar{X}_{10}$	S_5	S_{10}
15 female	7.68	7.90	6.93	6.53	10.48	11.46	7.33	8.08	13.63	14.83	11.28	10.48	28.24	29.22	17.58	18.38
15 male	29.22	27.62	19.36	18.78	40.67	41.07	22.73	23.31	46.80	48.00	25.04	25.66	71.71	77.03	39.69	74.73
All	17.56	18.16	17.58	17.36	25.09	25.89	22.51	22.91	29.61	30.81	25.49	25.49	49.20	52.35	37.12	25.89

S.D. = standard deviation

Table 3. Forces exerted (in N) at four requested levels by 15 female and 15 male subjects

Subjects	25% Level			50% Level			75% Level			100% Level		
	Mean	S.D.	CV	Mean	S.D.	CV	Mean	S.D.	CV	Mean	S.D.	CV
15 female	25.71	11.88	0.46	39.72	17.12	0.43	47.53	19.22	0.40	88.34	34.56	0.39
15 male	73.39	35.45	0.48	98.92	41.77	0.42	119.34	46.04	0.39	187.35	76.64	0.41
All	49.55	35.58	0.72	69.34	43.50	0.63	83.44	50.31	0.60	137.84	77.35	0.56

CV = S.D./Mean

Table 4. Actually exerted strength percentages

Requested level	Actually exerted percentages	
	Mean	95% Confidence limits
100	100[a]	$80 \leq \times \leq 120$
75	60.3	$47 \leq \times \leq 74$
50	50.3	$39 \leq \times \leq 62$
25	35.9	$27 \leq \times \leq 45$

[a] by definition

Table 5. Correlation coefficient (r) statistics after 5 and 10 repeated exertions at each strength level

Subject	r_5	r_{10}	Significant ($\alpha \leq 0.01$)
1	0.7930	0.8641	yes
2	0.7169	0.6662	yes
3	0.7975	0.7396	yes
4	0.7432	0.7863	yes
5	0.8754	0.8330	yes
6	0.8264	0.9191	yes
7	0.8255	0.8026	yes
8	0.8561	0.8543	yes
9	0.1123	0.3191	no
10	0.7392	0.6631	yes
11	0.8462	0.8653	yes
12	0.7191	0.8101	yes
13	0.8944	0.9548	yes
15	0.5175	0.6736	yes
16	0.8864	0.8879	yes
17	0.8048	0.8201	yes
18	0.5848	0.6730	yes
19	0.3172	0.3180	no
20	0.8503	0.8260	yes
21	0.8020	0.8425	yes
22	0.8177	0.7724	yes
23	0.8375	0.8329	yes
24	0.6868	0.7943	yes
25	0.7808	0.8182	yes
26	0.6927	0.8344	yes
27	0.7143	0.8044	yes
28	0.7984	0.8156	yes
29	0.8319	0.9237	yes
30	0.9118	0.9678	yes
Group r	0.775	0.816	yes
95% Confidence limits	$0.569 \leq r_5 \leq 0.880$	$0.644 \leq r_{10} \leq 0.911$	

All subjects were instructed to exert elbow flexion strengths at 100%, 75%, 50%, and 25% of their individual maximal capability. However, the subjects did not receive any external feedback about their actual strength scores. Each subject exerted 10 contractions under each condition with the sequence of exertions arranged to avoid ordering or fatigue effects.

All subjects were students of Wayne State University. None had physical disabilities relevant to the tests. Fifteen women and 15 men participated in this study. They were paid by the hour for their participation. (For more detail see Marras and Kroemer 1979.)

Results

While the results of the pilot study have been reported elsewhere (Marras 1978), the findings of the experiments in the main study are summarized in Tables 2–4. Table 2 shows the average onset slopes calculated using the results of the first five and of all ten trials, for all subjects, at the four requested levels, i.e., 25, 50, 75, and 100% of MVC. The results are given for the 15 female and 15 male subjects separately, and combined.

Table 3 lists the mean forces exerted at the four requested strength levels. The table also contains the standard deviations, and coefficients of variation (standard deviation divided by mean). Each value is based on the ten trials except for one subject who completed only five tests.

Since subjects did not receive any feedback about their exerted strengths, it is of interest to note what percentages they actually exerted. Table 4 provides that information, indicating the mean percentages and the 95% confidence limits calculated assuming normality of the data.

Table 5 lists the correlation coefficients between the onset slopes and the exerted percentages of strength, calculated for each subject, based on five or ten trials.

Discussion

As usual in strength testing, the female subgroup showed, on the average, lower forces exerted than the male subject group. However, otherwise no systematically different patterns in the data could be distinguished. Therefore, the data of men and women have been pooled in Tables 4 and 5.

The slopes of force build-up (Table 2) show a clear pattern, being flatter at the lower levels of exerted force and steeper at MVC. This result supports the experimental hypotheses nos. 1 and 2.

The relationships between slope and exerted force (Table 5) reinforce that finding. All but two subjects show significant and high positive correlations. Furthermore, the coefficients of correlations calculated after the first five exertions (r_5) show the same pattern as the coefficients computed using all ten data points (r_{10}). This indicates that about five repetitions should be sufficient to obtain reliable data. However, the coefficients calculated after ten exertions are higher and exhibit less variability as a group than the coefficients calculated after five exertions.

Each subject had been requested to exert 25, 50, and 75% of his/her MVC. The actual fraction of MVC usually deviated considerably from the required levels (Tables 3 and 4) as the subjects found it difficult to exert the requested force without external feedback about the existing level. In this respect, these subjects were in the same positions as persons trying to present repeated exertions at a chosen level with the intention of making the experimenter believe that they were MCVs. Beck and Hettinger (1956) and Rohmert and Sieber (1960) reported that a subject showed high variability in repeated exertions at low levels of strength exertion, and little variability at MVC[1]. In contrast, however, our data obtained from a larger number of subjects do not show any systematic pattern in that variability. The coefficients of variation (Table 3) are indeed remarkably constant for each subject group, and all subjects combined, at all four force levels. Statistical analyses (*F*-tests and *t*-tests) performed on the forces exerted as well on the percentages of MVC substantiated that there were no significant differences at the various strength levels. Hence, hypothesis no. 3 is not supported by the experimental findings.

Conclusions

The results of this study are interesting in three respects.

1. Rebuttal of hypothesis no. 3 makes the long-held assumption questionable that submaximal exertions, presented by a "cheating subject" as maximal efforts, can be detected by their large variability in repeated tests. Further experiments are underway to probe this problem.

2. Although the speed of strength build-up is highly individual, the experiments indicate that the onset slopes of strength exertions may provide a highly reliable indicator of the actual levels (percentages of MVC) exerted. It appears that the strength formation phase has been generally overlooked in the past as a possible source of information about the authenticity of a static strength exertion.

3. Lastly, these results suggest an interesting application in routine strength testing. It might be feasible to use simply a recording dynamometer to assess whether or not a subject actually exhibits maximal voluntary exertions. After the subject performed repeated tests at several requested force levels of the individual's strength capability (without external feedback about the actually exerted strength), one would simply observe the slope of force build-up for each exertion. The steeper the build-up, the higher the probability that indeed an MVC was performed. Obviously, this procedure requires that the Caldwell regimen is used. Further experiments may show whether or not this simple method is reliable.

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1 It should be pointed out, however, that the earlier researchers probably used experimental techniques somewhat different from the regimen applied here. However, a comparison is difficult because the instructions to the subjects were not completely described in the earlier reports. This underlines the need for a standardized regimen to be followed, such as the Caldwell procedure

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