

ABSTRACT: The purpose of this investigation was to describe the relationship between the central activation ratio (CAR) and the percent maximum voluntary effort (% MVE) during isometric quadriceps femoris contractions. Twenty-one healthy, young adults participated in three test sessions. During each session, one of three train types was tested: a 100-Hz 120-ms train, a 100-Hz 250-ms train, or a 50-Hz 500-ms train. Subjects were seated on a force dynamometer and stabilized to perform a 3–5-s isometric knee extension at MVE. Force targets were set at 25, 50, 75, and 100% of the MVE. With 5 min rest between efforts, subjects produced forces at the specified target levels. When each target was reached, the test train was delivered to quantify the amount of central activation. There were no significant differences in CARs across train types during maximal efforts, but during submaximal efforts at 25 and 50%, the 100-Hz 250-ms and 50-Hz 500-ms trains produced significantly lower CARs than the 100-Hz 120-ms train. The relationship between the CAR and the %MVE was curvilinear and best described by a second-order polynomial for all three train types. If tests of central activation are going to be used clinically, it is important to know the relationship between the CAR and voluntary effort; however, further study will be required to extend these results to specific patient populations.

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MEASUREMENT OF CENTRAL ACTIVATION FAILURE OF THE QUADRICEPS FEMORIS IN HEALTHY ADULTS

SCOTT K. STACKHOUSE, MSPT, JESSE C. DEAN, BS, SAMUEL C.K. LEE, PhD,
and STUART A. BINDER-MACLEOD, PhD

Department of Physical Therapy, University of Delaware, 315 McKinly Laboratory,
Newark, Delaware 19716, USA

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Muscle contraction is a phenomenon that requires central and peripheral activation processes. Failure anywhere along the steps of central or peripheral activation can result in fatigue or decrements in force production.^{4,10,12,13,18} Central activation failure can reduce the force output of a muscle by not recruiting all motor units or not attaining the maximal discharge rate from those motor units that are recruited.¹³

Merton was one of the first to test for failure of central activation.¹⁶ He used an electrically elicited, supramaximal tetany delivered to a relaxed muscle and a supramaximal twitch superimposed on a maximum voluntary muscle contraction (twitch-interpolation method) to assess the subjects' ability to activate

fully their adductor pollicis muscles. In the first method, he compared the force from a maximum voluntary isometric contraction to the force elicited by a supramaximal stimulus that produced tetany. He found no differences in force output between the electrical and voluntary contractions. In the second method, the muscle was stimulated with a supramaximal electrical pulse during a maximum voluntary isometric contraction and several submaximal contractions. Because the electrical activation of muscle was from a site proximal to the neuromuscular junction, any increment in force from the electrical stimulus suggested that the motoneuron pool was not activated maximally (i.e., suggested a failure of central activation). The size of the superimposed twitch force was plotted against the voluntary tension, and he demonstrated that as the voluntary tension increased, the superimposed twitch force decreased in a linear fashion. Thus, during maximal voluntary efforts, the muscle was assumed to be activated fully, because the electrical stimulus did not

Abbreviations: ANOVA, analysis of variance; CAR, central activation ratio; MVE, maximum voluntary effort

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Correspondence to: S.A. Binder-Macleod; e-mail: sbinder@udel.edu

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create an increment in force during the maximal contraction.

Another method for assessing central activation was developed by Newham et al.¹⁸ Their method was a modification of the twitch-interpolation technique; the single supramaximal pulse was replaced with a train of supramaximal pulses (burst). Like the single pulse, this train of pulses was superimposed (burst superimposition) on maximum voluntary contractions and resulted in enhanced resolution of the electrically induced force production during isokinetic testing of the quadriceps femoris. Both the twitch-interpolation and burst superimposition techniques have been used to describe muscle activation.^{1,3,13,16,18,22}

The ability to activate a muscle completely in the nonfatigued state has previously been demonstrated by some investigators^{3-5,10,11,14,16,21} but not by others.^{1,7,8,13,18,19,23-26} Differences in results between investigators may be a result of their method of detection. Merton¹⁶ demonstrated full activation of the adductor pollicis while using the twitch-interpolation method. The twitch-interpolation technique, however, may not be appropriate to use for every muscle group. For example, Belanger and McComas³ stated that full activation of the tibialis anterior was achieved using the twitch-interpolation method. However, in Figure 3 of their article, it is clear that this method is insensitive at high levels of activation because the superimposed twitch torque reaches zero at 90% of maximum voluntary torque.³

Three studies have compared the ability of the twitch-interpolation and the burst superimposition techniques to detect central activation failure during a maximum voluntary isometric contraction. Strojnik²⁴ compared a single pulse, a 100-Hz 50-ms train, a 100-Hz 100-ms train, a 100-Hz 150-ms train, and a 100-Hz 200-ms train and discovered no further decrement in central activation for trains longer than 100 ms in duration.²⁴ Similarly, Kent-Braun and Le Blanc¹³ compared the relative ability of a single pulse, a two-pulse train (20-ms interpulse interval), a 50-Hz 500-ms train, and a 50-Hz 1,000-ms train to detect central activation failure in the tibialis anterior. The high-frequency bursts showed instances of central activation failure, whereas the single pulse or the two-pulse train did not reveal any instances of central activation failure.¹³ Miller and colleagues¹⁷ compared three different 100-Hz trains (100, 200, and 300 ms), at producing increments in torque during contractions of approximately 80% of their subjects' maximal effort. Their results were similar to those of Strojnik,²⁴ because they found no further increments in torque for trains longer than 100 ms.

Therefore, when using the burst superimposition technique, high-frequency trains should be at least 100 ms in duration to obtain the maximum force or torque increment from the burst.¹⁷ There is, however, no literature on what frequency (50 or 100 Hz) is best for detection of central activation failure in human muscle.

The quantitation of central activation may have significant implications for clinical practice in rehabilitation. Measures of central activation have been used to detect central vs. peripheral strength deficits in the elderly, in people with injury to the anterior cruciate ligament and in people with chronic fatigue syndrome.^{7,9,15,23} Quantitation of central activation has typically been calculated by two different methods. In one, the activation level is calculated by dividing the superimposed twitch force by the resting twitch force (twitch-interpolation technique).^{3,20} The other method, termed the central activation ratio (CAR), was developed to quantitate central activation when using the burst superimposition technique.¹³ The CAR is calculated by dividing the maximum voluntary force prior to the delivery of the stimulation train by the maximum force produced during the superimposition of the train.¹³ In this method, a CAR of 1.0 equates to complete activation of the muscle, and any CAR <1.0 represents incomplete central activation.

Most previous studies have only investigated the degree of central activation at maximum efforts. The relationship between the CAR and voluntary effort, however, has never been studied while using the burst superimposition technique. Hence, the relationship between the CAR and voluntary effort is not presently known. Thus, the purpose of this study was to describe the relationship between the CAR and voluntary effort while subjects produced force levels equivalent to 25, 50, 75, and 100% of their maximal efforts.

METHODS

Subjects. We recruited 23 healthy subjects (10 men, 13 women) ranging in age from 20 to 35 [mean 25.6 ± 5.3 (SD) years] from a sample of convenience for this study. The study was approved by the University of Delaware Human Subjects Review Board, and all subjects read and signed informed consent forms.

Experimental Setup. Subjects were seated on a KIN-COM III dynamometer (Chattecx Corp, Chattanooga, Tennessee) as shown in Figure 1. The subjects' hips were flexed to approximately 85° and their knees flexed to 90°. The axis of the dynamom-

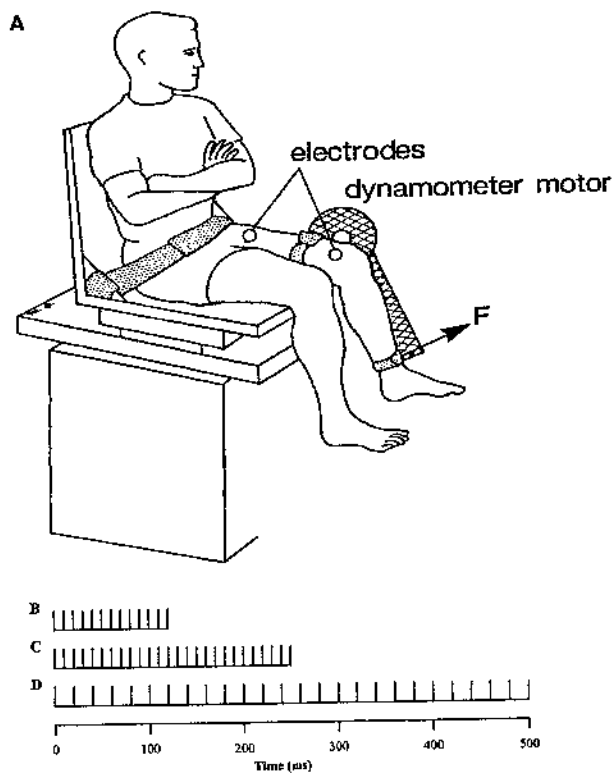


FIGURE 1. Schematic drawing (A) of the experimental set-up used to isometrically test the quadriceps femoris muscle. The subject's knee joint axis was aligned with the axis of the dynamometer, and set for isometric testing at 90° of knee flexion. Schematic diagrams of the three different trains used for the burst superimposition technique: (B) 100-Hz 120-ms, 13-pulse train; (C) 100-Hz 250-ms, 26-pulse train; and (D) 50-Hz 500-ms, 26-pulse train.

eter was aligned with the lateral femoral condyle. The lower leg, thigh, pelvis, and torso of the subject were stabilized by the force transducer pad, a thigh strap, a seat belt across the pelvis, and a Velcro strap across the chest. The quadriceps femoris muscle was stimulated using a Grass S8800 stimulator with a Grass model SIU8T stimulus isolation unit (Grass Instruments, West Warwick, Rhode Island). All stimulation pulses were 600 μ s in duration and the voltage dial set at 135 V. The SIU8T stimulus dial was placed on 20 with the intensity switch on *HI*. Two 7.6 cm by 12.7 cm self-adhesive electrodes (Conmed Corp, Utica, New York) were placed on the thigh. The anode was placed over the rectus femoris and the cathode over the vastus medialis. The positions of the electrodes were adjusted to permit stimulation over the motor points. Two prior investigations demonstrated no difference in the detection of central activation using the twitch interpolation technique with stimulation over the motor points of the quadriceps femoris and stimulation of the femoral nerve

within the femoral triangle.^{2,21} The stimulator was driven by a personal computer using customized software (LabView 4.0.1, National Instruments, Austin, Texas) to control the timing parameters of each stimulation protocol. Data were digitized at 200 samples per second and analyzed with custom-written software.

Experimental Sessions. All subjects participated in three testing sessions. Sessions were separated by at least 48 h, and subjects were asked to refrain from strenuous exercise for 24 h prior to each session. All sessions were identical except for the stimulation train used. Only one of the three test trains was used during each session, and the order was randomized for each subject. The test trains used for the burst superimposition were a 13-pulse, 100-Hz 120-ms train, a 26-pulse, 100-Hz 250-ms train, and a 26-pulse, 50-Hz 500-ms train (see Fig. 1). These trains were selected based on their use in prior investigations of central activation.^{13,18,22} Although, these frequencies are higher than observed during voluntary activation, high frequencies are needed to produce maximum tetanic contraction force from human quadriceps femoris muscle.^{6,20} In each test session, the subject was first asked to perform a 3–5-s voluntary contraction at an intensity perceived as 50–75% of maximal effort. This contraction served to familiarize the subject with the apparatus. After a brief rest, the subject performed a 3–5-s maximum voluntary effort (MVE) during which the train being tested was superimposed on the contraction at supramaximal intensity. If the CAR was less than 0.95, the subject was encouraged to kick harder, and after a 5-min rest period, the procedure was repeated. Each subject was given three attempts to reach a CAR \geq 0.95. If a CAR of at least 0.95 was not reached in three attempts, the subject was given the option to reschedule another test session to attempt to meet the criterion or to drop out of the study. Once a CAR of 0.95 was reached and after a 10-min rest period, the voluntary force produced during the MVE was used to set force targets at 25, 50, 75, and 100% of the maximum force. The force feedback from the KIN-COM dynamometer was used to display these targets visually for the subjects. With 5-min rest between contractions, subjects produced forces at the specified target levels. When subjects reached a stable force plateau at each target, the test train was delivered to the quadriceps to quantify the amount of central activation. The final effort at 100% of the MVE was used to determine whether the subject fatigued during the test. If the force level produced by the final MVE was not within 10% of the force of the

original MVE, the data were discarded. If a session was discarded due to fatigue, the session was rescheduled.

In a subset of four subjects (two men, two women), the ratio of the electrically elicited force at rest to the MVE force was determined on a separate day of testing. First, we determined each subject's CAR during a MVE as described above. All of the subjects attained CARs ≥ 0.95 . After resting for 5 min, the subjects performed a 3–5-s MVE to potentiate the muscle. Approximately 2–3 s after relaxation, one of the test trains was delivered (100-Hz 120-ms, 100-Hz 250-ms, or 50-Hz 500-ms). The subject then rested for 5 min. After this rest, the subject repotentiated the muscle with an MVE, and the second test train was delivered. This procedure was then repeated a third time for the third test train.

Data Analysis. The CAR was calculated as the maximum voluntary force produced prior to delivery of the train divided by the maximum force produced during the superimposition of the train. A one-way repeated measures analysis of variance (ANOVA) compared the CARs attained using the three different train types during contractions at 25, 50, 75, and 100% effort. If a significant main effect was found for train type, Tukey HSD post-hoc testing was performed to identify differences between trains. Also, the relationship between the CAR and MVE was plotted, a line of best fit was calculated for each train type, and a regression analysis was performed to calculate the coefficient of determination (r^2).

RESULTS

Raw force traces from a typical subject are presented for the initial MVE and the subsequent trials at different levels of effort (Fig. 2). Of the 23 subjects, 21 were able to attain a CAR of 0.95 or greater within three trials for the initial MVE. Of the two subjects who did not reach a CAR of 0.95, one did not reschedule another session and the other failed to meet the CAR criteria during the second session and was subsequently dropped from the study. Of the 21 subjects who completed the study, two subjects repeated a session due to a drop in force (fatigue) that was greater than 10% between the initial and final MVE.

The electrically elicited forces produced by the 100-Hz 120-ms, 100-Hz 250-ms, and 50-Hz 500-ms trains at rest were 55.0, 67.5, and 69.8% of the MVE force, respectively. During the initial MVE, the mean (\pm SD) CARs for the 100-Hz 120-ms, 100-Hz 250-ms, and 50-Hz 500-ms trains were 0.987 ± 0.017 , 0.976 ± 0.019 , and 0.982 ± 0.020 , respectively. Similarly, the mean (\pm SD) CARs during the final MVE trial for the 100-Hz 120-ms, 100-Hz 250-ms, and 50-Hz 500-ms trains were 0.971 ± 0.036 , 0.964 ± 0.042 , and 0.959 ± 0.062 , respectively (Fig. 3). There were no significant within-subject differences in CARs for either the initial MVE or the final MVE trials across train types (Fig. 3). Significant within-subject main effects for train type occurred at 25 and 50% efforts, but not at 75% effort. The differences between the CARs at 25 and 50% efforts were relatively small, however (i.e., range at 25% was 0.38–0.44 and at 50% was 0.67–

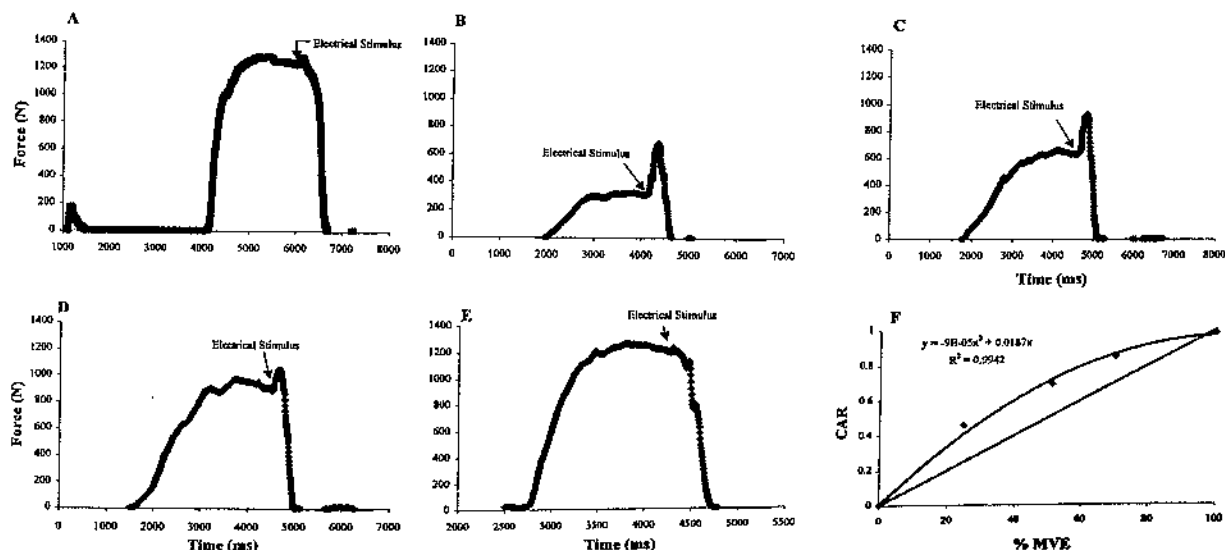


FIGURE 2. Typical raw force traces from an individual subject during the protocol using the 100-Hz 120-ms train. The initial MVE (A) and final MVE (E) have relatively small force increments due to the burst superimposition. Contractions at 25% (B), 50% (C), and 75% (D) of the MVE and their force increments due to the burst are shown. Plot of this subject's CAR–%MVE relationship against an identity line is shown in (F).

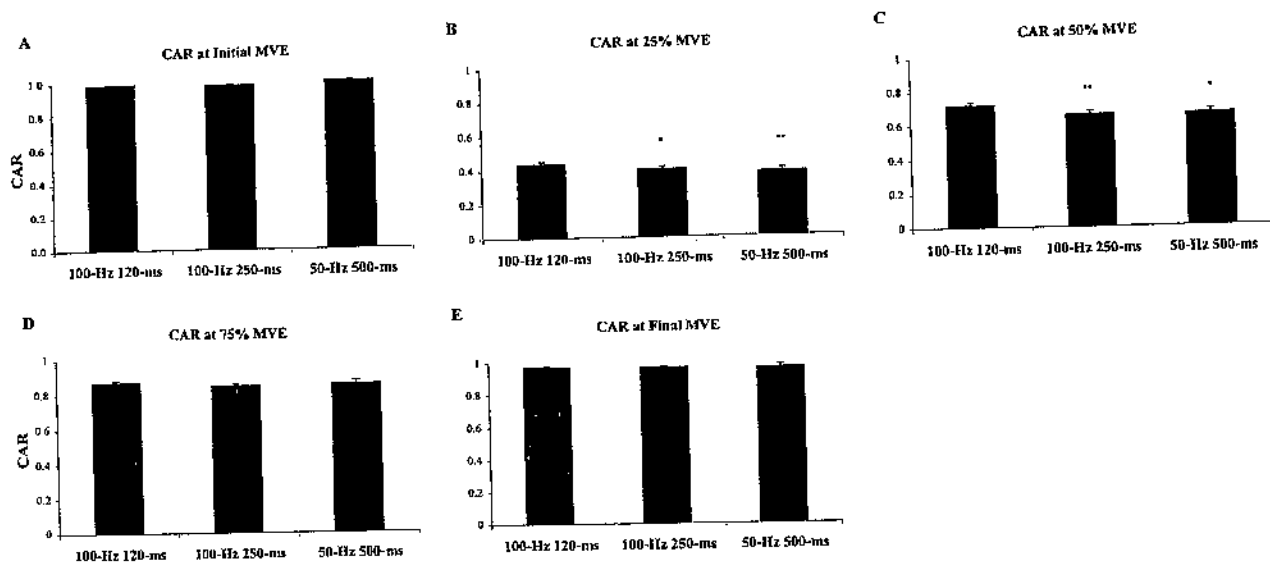


FIGURE 3. The mean CARs were compared between each test train for the initial MVE (A), 25% MVE (B), 50% MVE (C), 75% MVE (D), and final MVE (E). No significant main effects were found for train type during the initial MVE ($F = 2.133$, $P = 0.134$), the final MVE ($F = 0.454$, $P = 0.583$) and at 75% effort ($F = 1.515$, $P = 0.232$). Significant main effects were found for train type during the 25% ($F = 8.694$, $P = 0.002$) and 50% efforts ($F = 7.158$, $P = 0.006$). The 100-Hz 250-ms and 50-Hz 500-ms trains produced significantly smaller CARs than the 100-Hz 120-ms train at 25 and 50% of the MVE. * $P < 0.05$; ** $P < 0.01$.

0.72). Additionally, all CARs during submaximal efforts at 25, 50, and 75% of the MVE overestimated the actual percent MVE of the contraction. As shown in Figure 4, the CAR reports higher levels of activation than anticipated based on the percent effort of the contraction. For example, in Figure 4A, when a contraction was performed near 25% of the MVE, the corresponding mean CAR was 0.44. Likewise, at 50 and 75% of the MVE, the mean CARs were 0.72 and 0.87, respectively.

When the CAR was plotted against the percent MVE, a curvilinear relationship was found. A line of best fit was calculated for the group data under each train type, and a second order polynomial was determined to fit the data better than a straight line. The r^2 values for the group data were 0.9804, 0.9754, and 0.9459 for the 100-Hz 120-ms, 100-Hz 250-ms, and 50-Hz 500-ms trains, respectively. When a line of best fit was calculated using data from individual subjects, all subjects demonstrated high r^2 values regardless of train type. The range of r^2 values for the 100-Hz 120-ms train were 0.9896 to 0.9999, the range for the 100-Hz 250-ms train were 0.9900 to 1, and the range for the 50-Hz 500-ms train were 0.9901 to 0.9999.

DISCUSSION

Evaluation of initial and final MVE trials revealed no statistically significant differences in the CAR among train types (100-Hz 120-ms, 100-Hz 250-ms, and 50-Hz 500-ms). This result confirms and extends the

earlier work of others.^{13,24} Strojnik²⁴ demonstrated that there was no further decrement in central activation from 100-Hz burst superimposition trains over 100-ms and less than 200-ms duration during maximum efforts of isometric knee extension, and this study supports his findings during maximal efforts. In addition, we tested a 50-Hz 500-ms train that contained the same number of pulses as the 100-Hz 250-ms train. We believed that the 50-Hz train would allow more time for the summation of force, and thus would produce CARs that were lower relative to the other two test trains. However, during MVEs with the burst superimposition technique, all three train types performed equivalently.

Consistent with the work of Miller and colleagues,¹⁷ who found that during contractions at 80% of maximum, the force augmentation for the 100-Hz electrical trains did not differ between train durations of 100–300 ms, the present data at 75% of the MVE showed that train duration did not improve detection of central activation failure. In contrast, evaluation of the CAR during submaximal efforts at 25 and 50% of the initial MVE revealed that the two longer-duration trains produced significantly lower CARs than the 100-Hz 120-ms train. These two longer-duration trains may have revealed greater central activation failure because they allowed more time for the summation of forces from motor units recruited by the stimulation train than the short 120-ms train. Thus, a larger stimulated force would lower

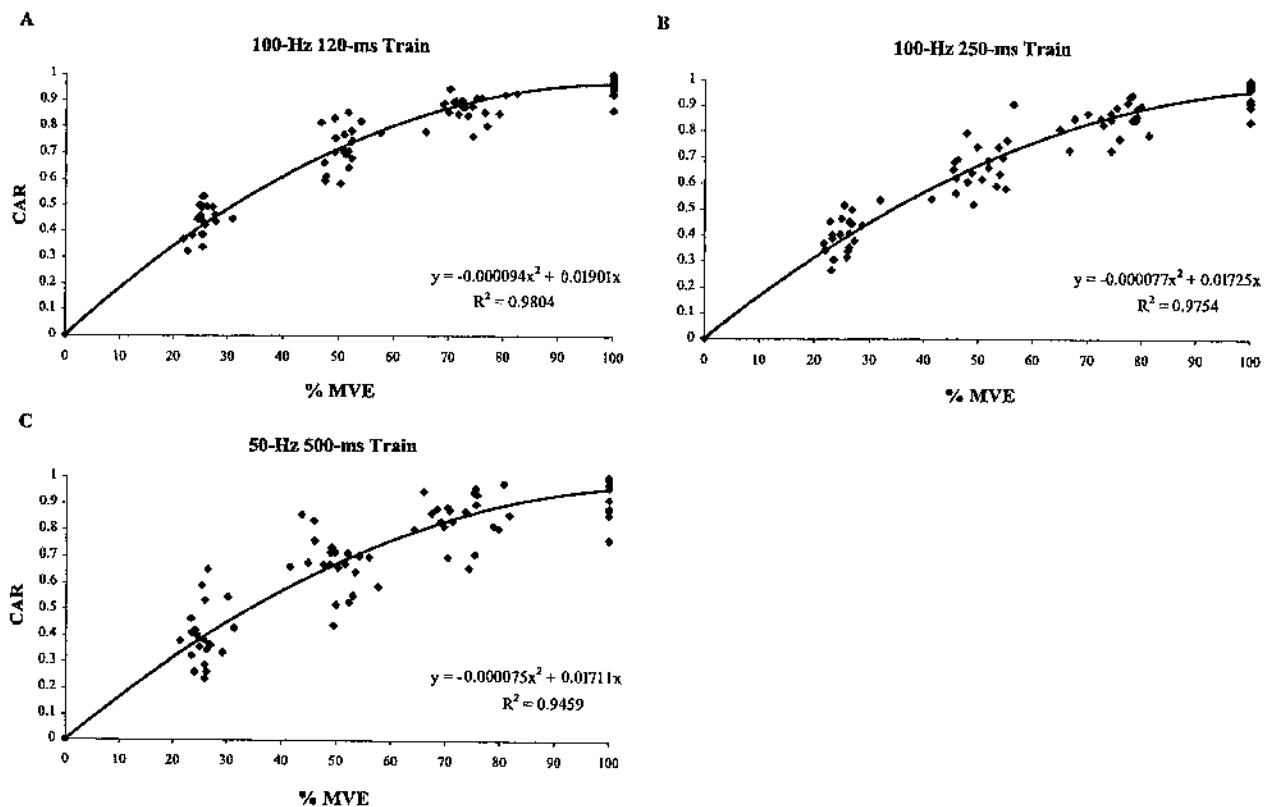


FIGURE 4. Group CAR data plotted as a function of the percent MVE for each test train (A–C). All three test trains exhibited a curvilinear relationship that was best fit by a second order polynomial.

the ratio between voluntary force and force produced during the superimposition.

When the relationship between the CAR and the percent MVE was examined, a second order polynomial was found to best fit the curvilinear relationship. High coefficients of determination (r^2 between 0.94 and 0.98) were obtained from the group data for each train type. The coefficient of determination indicated how much of the variance in the CAR can be explained by a change in the percent of MVE. An $r^2 = 0.9804$ for the group data using the 100-Hz 120-ms train, therefore, means that approximately 98% of the variance in the CARs can be accounted for by the variance in the percent MVEs. Thus, we have 98% of the information needed to make an accurate prediction of the CAR if we know the percent MVE.

The curvilinear relationship between the CAR and the percent MVE was a common feature for all tested train types (Fig. 4). A curvilinear relationship has been previously reported when the superimposed twitch torque (expressed as a percent of the resting twitch) is plotted as a function of the voluntary torque or the percent maximum voluntary contraction in studies employing the twitch-interpolation technique.^{2,3,8,19,21} We assumed that the CAR

should be equivalent to the voluntary effort, because the CAR was a measure of central activation. As shown in Figure 4, however, the CAR suggested that the muscle was more highly activated than the percent MVE suggested during submaximal contractions (25, 50, and 75%). In addition, the curvilinear shape indicates that the CAR may be an insensitive measure at high voluntary efforts (>90% MVE) secondary to being at the flat portion of the curve (Fig. 4A).

The CAR overestimated the percent MVE because the stimulated force did not bring the force level up to the initial MVE. The stimulated force in Figure 2B did not equal the voluntary force in Figure 2A. The CAR, therefore, overestimates the percent MVE compared to an identity line (slope of 45°; Fig. 2F). If the electrical train allowed time for full summation of force, we posit that a linear relationship (slope of 45°) would exist between the CAR and the percent MVE. However, shorter trains are used in the burst superimposition technique to increase subject comfort. In an effort to test whether the relationship between the CAR and percent MVE can be made into an identity line, we tested one volunteer subject using a 100-Hz 1,000-ms train. While at rest, this burst was capable of producing 85.7% (1,443 N)

of the subject's MVE (1,683 N). The relationship between the CAR and the percent MVE (25, 50, 75, and 100%) was much closer to a linear relationship for this subject than if a 100-Hz 120-ms train was used. The coefficients of determination for linear and second-order regressions were 0.97 and 0.99, respectively. In fact, the linear regression equation virtually superimposed over an identity line between the CAR and percent MVE. The pilot data from this subject support our belief that the curvilinear relationship between the CAR and percent MVE is secondary to the burst not being able to produce the maximum force from the muscle.

If tests of central activation are going to be used clinically, it is important to know the relationship between the CAR and voluntary effort. In the present study, a CAR of 0.80 was seen when subjects only produced approximately 60% of their MVE (see best-fit line of 100-Hz 120-ms train; Fig. 4A). Thus, if a linear rather than the presently curvilinear relationship is used to interpret the CAR, clinicians may markedly underestimate a patient's deficit in force production that results from central activation failure. Further studies, however, are required before the present results can be extended to specific patient populations.

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