Motor-Unit Synchronization Alters Spike-Triggered Average Force in Simulated Contractions

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Taylor, Anna M., Julie W. Steege, and Roger M. Enoka. Motor-unit synchronization alters spike-triggered average force in simulated contractions. J Neurophysiol 88: 265–276, 2002; 10.1152/jn.01013.2001. The purpose of the study was to quantify the effect of motor-unit synchronization on the spike-triggered average forces of a population of motor units. Muscle force was simulated by defining mechanical and activation characteristics of the motor units, specifying motor neuron discharge times, and imposing various levels of motor-unit synchronization. The model comprised 120 motor units. Simulations were performed for motor units 5–120 to compare the spike-triggered average responses in the presence and absence of motor-unit synchronization with the motor-unit twitch characteristics defined in the model. To synchronize motor-unit activity, selected motor-unit discharge times were adjusted; this kept the number of action potentials constant across the three levels of synchrony for each motor unit. Because there was some overlap of motor-unit twitches even at minimal discharge rates, the simulations indicated that spike-triggered averaging underestimates the twitch force of all motor units and the contraction time of motor units with contraction times longer than 49 ms. Although motor-unit synchronization increased the estimated twitch force and decreased the estimated contraction time of all motor units, spike-triggered average force changed systematically with the level of synchrony in motor units 59–120 (upper 90% of the range of twitch forces). However, the reduction in contraction time was similar for moderate and high synchrony. In conclusion, spike-triggered averaging appears to provide a biased estimate of the distribution of twitch properties for a population of motor units because twitch fusion causes an underestimation of twitch force for slow units and motor-unit synchronization causes an overestimation of force for fast motor units.

INTRODUCTION

The twitch forces exerted by individual motor units can be estimated by artificially activating single motor axons or by extracting the contribution of single motor units to the net force during a voluntary contraction. The artificial activation methods that can be used in humans include intraneural stimulation (Westling et al. 1990), percutaneous stimulation (Doherty and Brown 1997; Sica and McComas 1971), and intramuscular microstimulation (Taylor and Stephens 1976). The extraction method is known as spike-triggered averaging (Buchthal and Schmalbruch 1970; Stein et al. 1972).

Each method has a number of strengths and weaknesses when used to characterize motor-unit properties in human subjects (Chan et al. 2001). As a consequence, there is some uncertainty over which technique provides the most accurate estimate of the twitch force of single motor units. For example, the principal limitation of the artificial activation techniques is that individual motor units are activated in an otherwise passive muscle, which attenuates the externally measured force (Clamann and Schelhorn 1988; Troiani et al. 1999). In contrast, concurrent activation of multiple motor units during a voluntary contraction distorts the twitch profile of a motor unit due to overlapping twitches and the presence of motor-unit synchronization (Elek et al. 1992; Milner-Brown et al. 1973; Stein and Yang 1990). Furthermore, both experimental approaches (artificial activation and extraction) generally provide insufficient detail on the distribution of properties across a population of motor units (Enoka and Fuglevand 2001).

The purpose of the study was to quantify the effect of motor-unit synchronization on the spike-triggered average forces of a population of motor units. We hypothesized that the correlated discharge of action potentials by motor units would superimpose twitch responses and distort the estimated motor-unit force that is obtained with spike-triggered averaging. We compared the twitch forces and contraction times of motor units in the presence and absence of physiological levels of motor-unit synchronization in simulated isometric contractions. We found that spike-triggered averaging does not provide a reasonable estimate of the motor-unit twitch and that this average is further distorted by motor-unit synchronization. Some of these effects were distributed across the entire population of motor units, whereas other effects were more focused. A preliminary account of these findings has been published in abstract form (Taylor et al. 2001).

METHODS

The computer simulations in this study used a model of a motor neuron pool that was initially developed by Fuglevand et al. (1993) and later modified to include motor-unit synchronization (Yao et al. 2000). Based on experimentally determined physiological properties of a human hand muscle, the model determined the activation pattern of the motor neuron pool in response to a prescribed level of excitatory drive and then used this activation pattern to predict the force exerted by the muscle. The pool comprised 120 motor neurons that were characterized by systematic variations in recruitment threshold, range of discharge rates, innervation ratio, conduction velocity of sarcolemmal action potentials, motor-unit territory, amplitude and duration of the twitch force, and the specific shape of the force-
frequency relation. Motor unit 1 had the lowest recruitment threshold, the longest contraction time, and the weakest twitch force, whereas motor unit 120 had the converse properties. All motor units began discharging at 8 Hz on recruitment. Motor unit 7 had a peak discharge rate of 35 Hz, and the maximal discharge rate of the other motor units in the pool decreased as a function of recruitment threshold to a value of 25 Hz for motor unit 120. At the time of recruitment of motor unit 120, motor unit 1 was discharging at 19.7 Hz.

Motor-unit synchronization

In addition to a control condition that involved no synchrony, moderate and high levels of motor-unit synchronization were imposed using an extension of Yao et al. (2000). Briefly, the model adjusted the timing of selected action potentials to impose a temporal association between some of the action potentials discharged by different motor neurons (Fig. 1). To accomplish this, one active unit was designated as the reference unit, and the action potentials discharged by other motor units were synchronized to a randomly selected proportion of the reference motor-unit discharges. The moderate level of synchronization involved selecting 10% of the action potentials discharged by the reference unit compared with 25% for the high level of synchronization. The action potentials that were discharged by other motor units (correlated units) were temporally aligned with the selected action potentials. The number of correlated motor units was prescribed by the relation

\[ s = i^{0.85} \]

where \( s \) is the synchronization proportion and \( i \) is reference motor-unit number. The result of this relation produced a timing adjustment of about one or two action potentials for each selected action potential of the reference motor unit. To be used as a correlated unit, the motor unit had to discharge an action potential within 15 ms of the reference discharge. The timing adjustment did not impose an exact coincidence with the reference action potential; rather, the time was adjusted based on a Gaussian distribution. The mean was the time of the reference discharge, with a SD of 1.67 ms. The imposition of synchronization across the pool for a given level of excitation was recursive and was repeated until every active motor unit had served as the reference unit.

In contrast to our previous model of motor-unit synchronization in which the adjustments were imposed on randomly selected motor units (Yao et al. 2000), the adjustments were distributed among motor units with similar recruitment thresholds (Datta and Stephens 1990; Schmied et al. 1994). To determine the motor units that could be selected for a timing adjustment, we constructed a normal probability distribution centered on each reference motor unit with a SD of 15 units (Fig. 1B). When standardized with a \( z \) transform, this distribution dictated the probability of selecting a particular motor unit to synchronize with a reference motor unit. Furthermore, the adjacent intervals between the discharge times of the correlated motor unit were constrained to be \( \geq 20 \text{ ms} \). Although synchronization was greater among similar motor units, the mean level of synchronization was uniform across the population (Fig. 1C).

Spike-triggered average force

To assess the effect of motor-unit synchronization on spike-triggered average force, we conducted 116 simulations, one for each motor unit from numbers 5 to 120. For each simulation, the level of excitatory drive to the motor neuron pool was set to recruit the motor unit of interest so that it discharged action potentials at the specified minimal rate of 8 Hz. The duration of each trial was 120 s. To determine the spike-triggered average force, an average was calculated from the cumulative sum of the net force that was measured for 50 ms prior to and 150 ms after the reference action potential. For most simulations, the intervals preceding and succeeding the reference action potential were required to have durations of \( \geq 110 \text{ ms} \) (Nordstrom et al. 1989). Based on these requirements, the spike-triggered average included a mean of 444 events in the absence of synchronization, 347 events for moderate synchrony, and 343 events for a high level of synchrony. There were fewer events used in the synchronization conditions because discharge times were more variable and fewer discharges met the requirement that the surrounding intervals be \( \geq 110 \text{ ms} \). The spike-triggered average forces were compared with the shape and parameters of a single impulse response of the model motor unit.

In addition, the fusion index (Bakels and Kernell 1995; Celickowski and Grottel 2001) was computed for every active unit during each simulation. A separate set of simulations were run with each unit activated at a constant rate that was equivalent to the mean rate at which it discharged during the spike-triggered averaging simulation. The fusion index was computed as the minimal force divided by the maximal force produced by the single motor unit (an index value of 1.0 indicates complete fusion).

Statistics

The level of synchrony imposed by the timing adjustments was quantified with the Common Input Strength (CIS) index between pairs of selected motor units (Nordstrom et al. 1992). The amount of motor-unit synchronization within the pool was quantified with the Population Synchrony Index (PSI), which indicates the total number of coincident action potentials for all active motor units in excess of that expected due to chance for independently activated units (Yao et al. 2000). A PSI of zero corresponds to the absence of an active process that increases the coincidental discharge of action potentials. Because there was little variation in the calculated statistics for the repeated simulations, we report the results for one simulation trial only for each condition.

To assess the accuracy of spike-triggered averaging, the forces obtained by spike-triggered averaging were compared with the model twitches. The model twitches can be considered as the twitch that would be evoked by electrical stimulation of a single motor unit. To facilitate the comparison, the 116 motor units were assigned to 1 of 10 groups based on twitch force. Each group comprised the motor units with peak twitch forces within 10 arbitrary unit (au): \( \leq 10 \text{ au} \), 11–20, 21–30, 31–40, 41–50, 51–60, 61–70, 71–80, 81–90, and 91–100 au. Due to the exponential distribution of twitch forces, the number of motor units that comprised each group varied, and the group that had forces \( \leq 10 \text{ au} \) was the largest. Two-factor ANOVAs with repeated measures on sampling condition were used to compare twitch forces between the model and spike-triggered averaging, and across levels of synchronization. One-way ANOVAs with Tukey post hoc tests were performed to test differences between levels of synchronization. Paired \( t \)-tests with a Bonferroni correction were used to examine significant differences between the model and spike-triggered averaging for each group. Similar statistical analyses were performed to evaluate the effects on contraction time with the 116 motor units assigned to 10 groups. For these comparisons, each group comprised motor units with contraction times within 6 ms: 90–85, 84–79, 78–73, 72–67, 66–60, 59–53, 52–47, 46–41, 40–35, and 34–29 ms. As with the distribution for twitch forces, contraction times are exponentially distributed across the population of model motor units. Therefore there were not a uniform number of motor units in each group.

RESULTS

The twitch response of all motor units in the pool was modeled as a critically damped second-order system (Milner-Brown et al. 1973). The distribution of peak twitch forces was represented as an increasing exponential function, whereas the relation between twitch force and contraction time (time to
peak force) was approximated as an inverse power function (Fuglevand et al. 1993). Based on these functions, the lowest threshold motor unit had a peak twitch force of 1 au and a contraction time of 90 ms, compared with a peak twitch force of 100 au and a contraction time of 30 ms for the highest threshold motor unit.

Effects of imposed synchronization on discharge rate

The mean interspike interval (ISI) in the basic model was 124.4 ms (8.04 Hz), and the mean coefficient of variation for discharge rate was 20%. With the adjustment of discharge times to impose different levels of synchronization, there was
a minimal change in the mean duration of the ISIs (124.5 ms, moderate; 124.8 ms, high synchrony). The coefficient of variation for discharge rate increased to 23.7% for moderate and 27.5% for high synchrony. In conjunction with the imposed synchronization, there was an increase in the mean coefficient of variation for force (3.4%, no synchrony; 3.9% moderate synchrony; 4.5%, high synchrony).

**Spike-triggered average force and contraction time**

Prior to examining the effect of motor-unit synchronization on the spike-triggered average force, we compared the model twitches with the responses obtained by spike-triggered averaging. The comparison is shown (Fig. 2) for representative low-threshold (30) and high-threshold (110) motor units. As suggested by these comparisons, the averaging procedure had a greater effect on the peak twitch force and contraction time of low-threshold units compared with high-threshold units. These effects on the twitch contraction time, peak twitch force, and the association between contraction time and peak force are quantified for the entire population of 120 motor units in Fig. 3. The range of

![Model twitch responses of motor units 30 and 110 compared with those obtained by spike-triggered averaging in the absence and presence of moderate and high levels of motor-unit synchronization. Spike-triggered averaging (thin line) had a greater effect on the modeled twitch profile (thick line) for motor unit 30 compared with motor unit 110. Both moderate (open circles) and high (filled circles) levels of motor-unit synchronization altered the twitch response of the 2 motor units as estimated by spike-triggered averaging.](http://jn.physiology.org/)

![Effects of spike-triggered averaging on peak twitch force (A), contraction time (B), and the association between contraction time and peak twitch force (C) as distributed across the population of 120 motor units. Each data point corresponds to the model twitch (gray symbol) and the spike-triggered average value (•) for a single motor unit. The y axis in A is a log scale to emphasize the underestimation of peak force for low-threshold motor units.](http://jn.physiology.org/)
model (23.6 ± 25.0, 2.8–100.0 au). The decrease in spike-triggered average force (P < 0.001) was significant for motor units with a peak twitch force <30 au (motor units 5–89), and for motor units with a peak twitch force between 50 and 60 au (motor units 103–106).

The range of contraction times (mean ± SD, range) specified in the model (53 ± 16, 30–86 ms; Table 1) was also reduced by spike-triggered averaging (41 ± 8, 26–68 ms) and distributed more uniformly across the population (Fig. 3B). However, not all motor units experienced the reduction in the estimated contraction time (P < 0.001 for the interaction term). Post hoc testing indicated that the decrease in estimated contraction time was limited to the motor units with contraction times >49 ms. These effects on the two twitch properties combined to substantially alter the association between twitch force and contraction time as estimated by spike-triggered averaging compared with the relation defined in the model (Fig. 3C).

Because experimental measurements of spike-triggered average force are sometimes performed at higher discharge rates, we also determined the estimated motor-unit force when the motor neuron discharged action potentials at 12 Hz. To achieve a sufficient number of events for the averages, however, we had to reduce the duration of the preceding and succeeding intervals from 110 to 80 ms. For comparison, we also performed simulations at the 8-Hz discharge rate with a spike-triggered averaging interval limit of 80 ms. These simulations were performed on every 10th motor unit (10, 20, 30...120) for a total of 12 simulations for each condition (Table 1). The spike-triggered average force evoked by a discharge rate of 12 Hz was depressed (42 ± 23, 9–76%) more than that for 8 Hz (72 ± 16, 43–95%) compared with the twitch values specified in the model. This attenuation in the 12-Hz force was largely due to an effect on the high-threshold motor units, as indicated by the reduction in the maximum value (76 vs. 95%). In contrast, a greater effect on low-threshold motor units caused the contraction time to be reduced for the 12-Hz condition (68 ± 27, 24–104%) than the 8-Hz condition (78 ± 12, 51–97%) compared with the isolated twitches from the model.

It was also possible to assess the effect of the duration of the surrounding intervals (80 vs. 110 ms) on the average values when the motor neuron was discharging at 8 Hz. The average force values were similar for the two conditions (Table 1), which meant the decrease relative to the model values was similar for the 80-ms (72 ± 16, 43–95%) and 110-ms (71 ± 25, 34–104%) conditions. The contraction times were briefer for the 80-ms condition (Table 1) and were reduced more (78 ± 12, 51–97%) than those for the 110-ms condition (85 ± 21, 49–133%) compared with the model twitches.

### Motor-unit synchronization

Spike-triggered averaging was performed on simulated forces after we had adjusted the timing of selected action potentials to impose moderate and high levels of motor-unit synchronization. For each selected action potential, this resulted in a timing adjustment of approximately one to two other action potentials (Fig. 1A). The cumulative total of these adjustments, however, was substantial. For example, when spike-triggered averaging was performed on the discharge times of motor unit 120, adjustments had been performed on 67% of the population action potentials during the 120-s simulation (Fig. 1B). The amount of synchrony corresponded to average values of CIS = 0.50 and PSI = 0.93 for the moderate level and CIS = 0.98 and PSI = 1.9 for the high level. The logarithmic increase in the number of adjusted events was necessary to maintain a uniform CIS value across the population (Fig. 1C). Cross-correlation histograms and cumulative sums (cusum) are shown for representative pairs of motor units in Fig. 4.

Both levels of synchrony qualitatively distorted the average motor-unit force extracted by spike-triggered averaging (Fig. 2). For the preferred averaging condition (8 Hz, 110 ms), the spike-triggered average force increased for both moderate synchrony (91 ± 33, 38–160%) and high synchrony (132 ± 46, 43–246%) compared with model twitches (Fig. 5A). The force estimated by spike-triggered averaging was significantly different for the three levels of synchronization (P < 0.001), and the interaction term was also significant (P < 0.001). The spike-triggered average force for the three levels of synchrony was statistically different for all groups except group 1 (motor units 5–89), where the high-synchrony condition was different to the no- and moderate-synchrony conditions. Thus motor-unit synchronization increased the spike-triggered force progressively for all motor units except those with the lowest recruitment thresholds.

There was a main effect (P < 0.001) for the level of synchrony on the estimated contraction times, with the values briefer for moderate synchrony (61 ± 16, 38–119%) and high

### Table 1. Modeled and spike-triggered average estimates of motor unit force and contraction time (CT) in the absence and presence of imposed synchronizations for four averaging conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>No. of Motor Units</th>
<th>Model Twitch</th>
<th>No Synchrony</th>
<th>Moderate Synchrony</th>
<th>High Synchrony</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 Hz, 110 ms</td>
<td>116 (5, 6, 7...120)</td>
<td>24 ± 25</td>
<td>20 ± 24</td>
<td>28 ± 37</td>
<td>40 ± 55</td>
</tr>
<tr>
<td></td>
<td>(3–100)</td>
<td>53 ± 16</td>
<td>(1–98)</td>
<td>(1–146)</td>
<td>(1–222)</td>
</tr>
<tr>
<td></td>
<td>(30–86)</td>
<td></td>
<td>42 ± 7</td>
<td>(22–62)</td>
<td>(22–68)</td>
</tr>
<tr>
<td>8 Hz, 110 ms</td>
<td>12 (10, 20...120)</td>
<td>27 ± 30</td>
<td>24 ± 29</td>
<td>34 ± 44</td>
<td>49 ± 67</td>
</tr>
<tr>
<td></td>
<td>(3–100)</td>
<td>52 ± 17</td>
<td>(1–93)</td>
<td>30 ± 4</td>
<td>26 ± 2</td>
</tr>
<tr>
<td></td>
<td>(30–82)</td>
<td></td>
<td>(30–52)</td>
<td>(1–144)</td>
<td>(2–222)</td>
</tr>
<tr>
<td>8 Hz, 80 ms</td>
<td>12 (10, 20...120)</td>
<td>27 ± 30</td>
<td>23 ± 29</td>
<td>34 ± 45</td>
<td>48 ± 65</td>
</tr>
<tr>
<td></td>
<td>(3–100)</td>
<td>52 ± 17</td>
<td>(1–95)</td>
<td>39 ± 7</td>
<td>26 ± 4</td>
</tr>
<tr>
<td></td>
<td>(30–82)</td>
<td></td>
<td>(28–48)</td>
<td>(2–155)</td>
<td>(2–217)</td>
</tr>
<tr>
<td>12 Hz, 80 ms</td>
<td>12 (10, 20...120)</td>
<td>35 ± 30</td>
<td>17 ± 22</td>
<td>34 ± 37</td>
<td>55 ± 62</td>
</tr>
<tr>
<td></td>
<td>(4–100)</td>
<td>52 ± 17</td>
<td>(1–69)</td>
<td>32 ± 9</td>
<td>28 ± 13</td>
</tr>
<tr>
<td></td>
<td>(30–82)</td>
<td></td>
<td>(18–54)</td>
<td>(12–133)</td>
<td>(18–64)</td>
</tr>
</tbody>
</table>

Data indicate the means ± SD (range) for motor unit force (arbitrary unit (au)) and contraction time (ms). The averaging conditions refer to the discharge rate of the motor unit (8 or 12 Hz) and the minimal duration of the preceding and succeeding intervals (80 or 110 ms).
synchrony (54 ± 15, 36–135%) compared with the model values (Fig. 5B). There was also a significant interaction (P < 0.001). With the exception of the lowest threshold motor units (motor units 5–7), the contraction times estimated with spike-triggered averaging were longer for the no-synchrony condition compared with the moderate- and high-synchrony conditions. In addition, the estimated contraction times for motor units 44–67 and 83–98 were longer with moderate synchrony compared with high synchrony. These results indicate that, in general, the estimated contraction time was briefer with motor-unit synchronization but there was not a systematic difference between moderate and high synchrony.

Because synchronization may not be distributed selectively across a population, we also performed one set of simulations in which there was no threshold-based selection of synchronized motor units. This meant that all active motor units had an equivalent probability of being selected for synchronization when the adjustments were made for each selected action potential. The simulations were performed on every 10th motor unit. The results indicated three differences between the spike-triggered average forces obtained with selective and uniform distributions of motor-unit synchronization. First, the increase in spike-triggered average force when motor units with similar thresholds were synchronized (Fig. 6). Second, the difference between the moderate and high synchrony conditions was similar for both selection schemes. Third, the spike-triggered average force of low-threshold units was altered with the uniform but not the selective distribution of synchronization.

The effect of synchronization on spike-triggered average force was quantified as the relation between the percentage increase in the force as a function of the CIS for a motor unit (Fig. 7). Because the force contributed by a motor unit is influenced by all the other motor units to which it is synchronized, we calculated the mean of the CIS values for the reference motor and the 15 preceding motor units whose discharges were most likely to be correlated with the reference unit according to the probability distribution (Fig. 1B). The CIS index was determined for moderate and high synchrony of every fifth motor unit, beginning with motor unit 15. The CIS index explained 57% of the variance in the increase in spike-triggered average force with motor-unit synchronization (Fig. 7A). There was not, however, a systematic effect of motor-unit synchronization, as indicated by the CIS index, on the variance in the estimated contraction time (Fig. 7B).

Spike-triggered average force was more augmented relative to the model twitch forces at a discharge rate of 12 Hz for moderate
synchrony (119 ± 77, 45–318%) and high synchrony (210 ± 141, 82–490%) compared with the average forces obtained at 8 Hz for moderate synchrony (102 ± 28, 50–155%) and high synchrony (141 ± 44, 61–217%). However, this effect was likely due to the increased CIS values that resulted from a greater number of adjustments associated with a discharge rate of 12 Hz; that is, the correlated activity among motor units was greater. Average contraction times were similar for the two discharge rates at moderate and high synchrony, but the range of contraction times was more compressed for the 8-Hz rate (Table 1). Similarly, there was a minor effect of interval duration (80 vs. 110 ms) on the spike-triggered average forces and contraction times for the two levels of synchrony (Table 1).

The influence of twitch fusion on spike-triggered averaging was quantified by comparing the fusion index of each motor unit with its spike-triggered average force. There was a strong correlation between the degree of twitch fusion of the reference unit and the underestimation of twitch force (Fig. 8A). However, twitch fusion did not modulate the effect of threshold-based distribution of synchronization on spike-triggered average force (Fig. 8B). In contrast, the uniform distribution of synchronization increased the mean amount of twitch fusion for large motor units and caused the mean fusion index in these simulations to be significantly associated with the large increase in spike-triggered average force (Fig. 8C).

**DISCUSSION**

The two main findings of this study are that the motor-unit responses obtained by spike-triggered averaging are different to the twitch properties of the motor units and that motor-unit synchronization further distorts these values. Although these effects have been reported previously, this study quantifies the effects of spike-triggered averaging and motor-unit synchronization on the Twitches of an entire population of motor units.

**Basis for model assumptions**

Two parameters in the model were based on assumptions regarding the physiological characteristics of synchronization: the selection of units whose action potentials were synchronized and the limit on the magnitude of the adjustment in discharge time. Because these parameters could have altered the outcome of the simulations, we describe the reasons for selecting these values.

In the model, there was a greater probability that motor units with similar properties would be synchronized (Datta and Stephens 1990; Huesler et al. 2000; Schmeid et al. 1994). For...
example, Datta and Stephens noted that when comparing the synchronization between motor units with similar recruitment thresholds, the index of synchronization increased in comparison with pairs of motor units with disparate recruitment thresholds. Because the difference in discharge rate between the reference and event unit was similar for all comparisons, the findings of Datta and Stephens cannot be attributed to inaccuracy in the index used (E) due to discharge rate (Nordstrom et al. 1992). Similarly, Schmied et al. found an inverse relation between the difference in the mean discharge rate of the motor units and the amount of synchronization between pairs of motor units. Because motor units with similar properties and recruitment thresholds are more likely to be discharging at similar rates, this supports a threshold-based selection of motor units. Furthermore, Heusler and colleagues report a greater incidence of synchronization between pairs of motor units with a similar recruitment threshold in comparison with pairs of motor units that have a larger difference in recruitment force.

Despite the relatively consistent finding that motor-unit synchronization indices are higher among pairs of motor units with similar recruitment thresholds and discharge rates, there is
The effect of discharge rate is to cause consecutive presence of correlated discharges among the active motor units, which is consistent with the simulation results for the high-synchrony condition. As suggested by Nordstrom et al. (1989), however, the increase in spike-triggered average force with a modest increase in discharge rate was due to the presence of correlated activity among motor units, which is consistent with the simulation results for the high-synchrony condition. Because the partial fusion of twitches during spike-triggered averaging attenuates the estimated contraction time of low-threshold motor units, there is a compression of the range of contraction times observed in a population of motor units. For example, Van Cutsem et al. (1997) found in a study of 514 motor units in the tibialis anterior muscle that contraction time is determined by spike-triggered averaging, declined only modestly as a function of recruitment threshold. In contrast, the contraction times of motor units in a muscle exhibit a five-fold range when the measurements are performed on isolated motor units in a passive muscle (Burke et al. 1973). One strategy that has been used to reduce the effect of partial fusion on the estimates of twitch properties from spike-triggered averages is to apply modeling techniques to correct the distortions (Andrassen and Bar-On 1983; Calancie and Bawa 1986; Lim et al. 1995). Although these approaches have been only partially successful at providing accurate measures of the underlying twitches, these findings emphasize the significant effect of partial fusion due to overlapping twitches on the spike-triggered averages as estimates of motor-unit twitches.

Spike-triggered average force and contraction time

Since the origin of the spike-triggered averaging technique (Buchthal and Schmalbruch 1970; Stein et al. 1972), it has been recognized that the sampled motor-unit forces are influenced by both the discharge rate of the motor unit and the presence of correlated discharges among the active motor units. The effect of discharge rate is to cause consecutive twitch responses to overlap and hence diminish the peak-to-peak amplitude of the average force, especially for slow contracting motor units (Andrassen and Bar-On 1983; Calancie and Bawa 1986; Kossev et al. 1994; Thomas et al. 1990). The effect appears to begin at rates of 2–4 Hz (Calancie and Bawa 1986; Kossev et al. 1994), which are less than the minimum rate that a motor unit can repetitively discharge action potentials during a voluntary contraction. Consistent with these experimental findings, the simulations indicated that low-threshold motor units experienced the greatest decrease in force and contraction time when the spike-triggered averages were compared with the model twitches. This similarity between the experimental results and the simulation data underscores the validity of the model (Fuglevand et al. 1993).

Due to the effect of discharge rate on the motor-unit forces obtained by spike-triggered averaging, some investigators impose temporal constraints on the rates that are accepted into the average. The typical strategy is to limit the duration of the preceding and succeeding intervals before an action potential can be used as a trigger event (Duchateau and Hainaut 1990; Milner-Brown et al. 1973). For example, Nordstrom et al. (1989) found for motor units in the masseter muscle that a preceding interval of 300–140 ms and a succeeding interval of 100–300 ms resulted in minimal fusion of the twitches. With briefer preceding intervals, however, the spike-triggered average force increased and contraction time decreased. The decrease in contraction time is consistent with the findings from a controlled stimulation protocol (Calancie and Bawa 1986) and the current simulation results, which indicated a greater effect on low-threshold motor units. In contrast, the increase in spike-triggered average force observed by Nordstrom et al. (1989) with briefer preceding intervals was contrary to both the stimulation study (Calancie and Bawa 1986) and the no-synchronization condition in the current simulation. As suggested by Nordstrom et al. (1989), however, the increase in spike-triggered average force with a modest increase in discharge rate was due to the presence of correlated activity among motor units, which is consistent with the simulation results for the high-synchrony condition.

J Neurophysiol • VOL. 88 • JULY 2002 • www.jn.org
Motor-unit synchronization

Another limitation of the spike-triggered averaging technique is that the procedure is applied during voluntary contractions when there is usually correlated activity among the motor units (Farmer 1998; Kamen and Roy, 2000; Nordstrom et al. 1992; Semmler 2002). To reduce contamination of the spike-triggered average due to such correlated activity (Dick 1990; Milner-Brown et al. 1973), the accompanying electromyographic records are sometimes scrutinized for the presence of motor-unit synchronization (Milner-Brown et al. 1973; Nordstrom et al. 1989; Thomas et al. 1987). No study, however, has quantified the effect of motor-unit synchronization within an entire population on the responses obtained by spike-triggered averaging.

To assess the effect of motor-unit synchronization on the spike-triggered average responses, we adjusted the timing of independently generated trains of action potentials to impose physiological levels of synchronization. Experimental measurements of synchrony between low-threshold motor units during low-force contractions indicate that we imposed moderate and high levels of correlated activity (Nordstrom et al. 1992; Schmied et al. 2000). These levels of synchronization, however, may be lower than those observed for high-threshold motor units or during high-force contractions (Kamen and Roy 2000). As we have reported previously (Yao et al. 2000), the simulated discharge times produced cross-correlation histograms and cumulative sums that are comparable to those observed experimentally (Davey et al. 1993; Nordstrom et al. 1992; Schmied et al. 2000). The imposed levels of motor-unit synchronization had a pronounced effect on the spike-triggered averages. The shapes of the averaged responses were altered qualitatively by synchronization (Fig. 2), which indicates that the unusual waveforms sometimes observed experimentally are likely due to the presence of motor-unit synchronization rather than discrimination error.

For each motor unit, we assessed the effects of discharge timing on both spike-triggered averages and the strength of discharge correlation with a commonly used synchronization index (CIS). The results indicated that motor-unit synchronization progressively increased the estimated twitch force of motor units 59–120 and decreased the estimated twitch contraction time of motor units 5–67. When correlated with the CIS index, it was clear that much of the variability in spike-triggered average force was due to the imposed motor-unit synchronization. Taken together, these results demonstrate that motor-unit synchronization modifies the spike-triggered average estimate of the motor-unit twitch.

Although the imposed synchronization, as assessed by the CIS index, accounted for ~57% of the variation in the increase of spike-triggered average force, there was not a direct association between these two variables. At least two factors can influence this relation. First, the CIS index is a measure of the correlated activity between pairs of motor units and not the synchronous activity of all motor units that can influence the mechanical response of the reference motor unit. Binder and Powers (2001) reported that there is a nonlinear relation between the amount of common input and two indices of synchronization (E and CIS). Furthermore, the indices of synchronization are less sensitive to changes in correlated discharge with lower levels of common input. The relative insensitivity of indices of synchronization could reflect either a nonlinearity in the response of neurons to common input or a lack of sensitivity of the cross-correlation histogram to the amount of correlated discharge. We adjusted discharge times to impose synchronization and still observed a nonlinear relation between the number of coincident discharges and synchronization. Consequently, our results suggest that a large part of the nonlinearity observed by Binder and Powers is related to insensitivity of the cross-correlation histograms to synchronous discharge.

Second, the amount of force increase in the spike-triggered average likely depends on the amount of variability between coincident discharges. Variability in the timing of coincident twitches would attenuate the amplitude of the summed twitch because the peak force of each twitch would not be reached concurrently. Accordingly, the force increase in simulations with no time-adjustment variability (results not reported here) was substantially larger for the same amount of synchrony.

The results indicate that although motor-unit synchronization shortened the spike-triggered average contraction times for the population of motor units, there was not a systematic relation between the level of synchronization and the change in contraction time. If the superimposed twitches were exactly coincidental, the number of superimposed twitches would not greatly alter the mean time to peak force. Therefore the effect of synchronization on contraction time is probably related to variability in the timing of coincident discharges rather than the number of coincident twitches. If the reference unit discharges slightly before or after the other active units, its twitch will be superimposed on either the rising or falling phase of the forces exerted by the other units. If multiple twitches were consistently included in the spike-triggered average for each unit, the values obtained across the population of motor units would be more similar, as indicated by the simulation results.

Twitch fusion and synchronization

The results of the computer simulations indicate that twitch fusion causes an underestimation of twitch force in motor units with long contraction times and that synchronization causes an overestimation of force in motor units with short contraction times. However, the interaction of twitch fusion and motor-unit synchronization also needs to be addressed. To do so, we first compared the accuracy of spike-triggered average force and the fusion index of each motor unit at recruitment. As expected, there was a significant association between the fusion index and the underestimation of twitch force. However, there was not a significant relation between the force increase due to synchronization and the mean fusion index of either the preceding 15 units or the mean fusion index for the whole population. This indicates that the increase in force observed in the presence of synchronization is independent of the mean fusion index of the synchronized units. This is probably due to the low discharge rates and consequent low levels of fusion for the motor units selected for synchronization.

In contrast, when no selection criteria were used to apply synchronization, there was a significant correlation between the mean fusion index for all active units and the increase in spike-triggered average force due to synchronization. Because the uniform distribution of synchronization resulted in an equal probability that all motor units could be synchronized, the mean fusion index for larger motor units was increased, which
would decrease spike-triggered average force. However, spike-triggered average forces were larger in this condition. This is likely due to the variability in the timing of synchronized discharges and the probability of a reference twitch being summed with either the rising or falling phase of the twitch from a synchronized unit. As the twitch fusion increases, twitch relaxation times become briefer. With the uniform distribution of synchronization, there was a greater probability that large motor units would discharge at the same time as smaller motor units. Because the smaller motor units have longer contraction times and discharge at higher rates, they would be more fused. Thus there is a greater probability that the reference discharge will occur when the force of the other unit is relatively high. Conversely, if the reference unit is synchronized with similar motor units, they will be discharging at lower rates and their twitches will be relatively unfused. As a result, there would be a higher probability that the reference unit will discharge when the force of the synchronized unit is decreasing; this would attenuate the amplitude of the spike-triggered average force.

Implications for experimental findings

To characterize the modulation of muscle force, it is important to know the distribution of twitch properties among the motor units that comprise the muscle. In humans, it is difficult to obtain a large enough sample to ensure adequate representation of the range of motor-unit properties in a muscle. The studies that have successfully represented an entire motor-unit population have used spike-triggered averaging to assess contractile properties (Van Cutsem et al. 1997). These data indicate that there are more low- than high-force motor units, that there is a narrow range of twitch contraction times, and that there is a poor correlation between twitch force and contraction time. This is contrary to the observations in experimental animals that there is a distinct inverse exponential relation between tetanic tension and contraction time (Burke and Tsairis 1974; McDonagh et al. 1980).

Findings such as these have caused investigators to pose the question: are the contractile properties of human muscle different from those in experimental animals (Bigland-Ritchie et al. 1998)? The results obtained from our computer simulations of spike-triggered averaging can help address this question. The model was based on the stereotypical distribution of motor-unit properties that has been observed in experimental animals, yet the results of spike-triggered averaging from this population were strikingly similar to the results from experimental work in humans. This suggests that it is reasonable to extrapolate the distributions of twitch characteristics measured in experimental animals to humans.

In summary, the computer simulations provide a comprehensive account of the population effects of partial fusion due to overlapping twitches and motor-unit synchronization on the responses obtained with spike-triggered averaging. The technique of spike-triggered averaging underestimates the twitch force and contraction time of low-threshold motor units. Superimposed on this effect, the correlated activity of motor units during a voluntary contraction progressively increases the estimated twitch force, especially of high-threshold motor units, and decreases the estimated contraction time of low-threshold motor units. These results underscore the suggestion that spike-triggered averaging in a muscle containing motor units with relatively long contraction times or with a moderate level of synchronization will likely result in an inaccurate estimate of the range of twitch properties possessed by the motor-unit population.

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