

Coherence at 16–32 Hz Can Be Caused by Short-Term Synchrony of Motor Units

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Submitted 16 November 2004; accepted in final form 28 February 2005

Moritz, Chet T., Evangelos A. Christou, François G. Meyer, and Roger M. Enoka. Coherence at 16–32 Hz can be caused by short-term synchrony of motor units. *J Neurophysiol* 94: 105–118, 2005. First published March 2, 2005; doi:10.1152/jn.01179.2004. Time- and frequency-domain measures of discharge times for pairs of motor units are used to infer the proportion of common synaptic input received by motor neurons. The physiological mechanisms that can produce the experimentally observed peaks in the cross-correlation histogram and the coherence spectrum are uncertain. The present study used a computational model to impose synchronization on the discharge times of motor units. Randomly selected discharge times of a unit that was being synchronized to a reference unit were aligned with some of the discharge times of the reference unit, provided the original discharge time was within 30 ms of the discharge by the reference unit. All time-domain measures (indexes CIS, E, and k') were sensitive to changes in the level of imposed motor-unit synchronization ($P < 0.01$). In addition, synchronization caused a peak between 16 and 32 Hz in the coherence spectrum. The shape of the cross-correlogram determined the frequency at which the peak occurred in the coherence spectrum. Further, the magnitude of the coherence peak was highly correlated with the time-domain measures of motor-unit synchronization ($r^2 > 0.80$), with the highest correlation occurring for index E ($r^2 = 0.98$). Thus the peak in the 16- to 32-Hz band of the coherence spectrum can be caused by the time that individual discharges are advanced or delayed to produce synchrony. Although the in vivo processes that adjust the timing of motor-unit discharges are not fully understood, these results suggest that they may not depend entirely on an oscillatory drive by the CNS.

INTRODUCTION

Two measures are often used to quantify the correlated discharge of action potentials by pairs of motor units: cross-correlation and coherence. Cross-correlation analysis is a time-domain measure that determines the proportion of coincidental discharge times by two concurrently active motor units (Bremner et al. 1991; Sears and Stagg 1976; Semmler 2002). A greater-than-chance number of coincidental discharges produces a central peak in the cross-correlation histogram and denotes the presence of motor-unit synchronization, which is likely to be caused either by branched common input to the spinal motor neurons (Datta et al. 1991; Kirkwood and Sears 1978; Sears and Stagg 1976) or by presynaptic synchronization due to common input to efferent fibers from the motor cortex (Baker et al. 2001; Smith and Fetz 1989). In contrast, coherence analysis is a frequency-domain measure that identifies the common frequency characteristics of the discharge times for the two motor units (Farmer et al. 1993a; McAuley et al. 1997; Rosenberg et al. 1989). It has been proposed that peaks in the coherence spectrum are a consequence of rhythmic descending

inputs onto the motor neurons from oscillators within the cerebral cortex or brain stem (Conway et al. 1995; Farmer et al. 1993a, 2004; Kakuda et al. 1999; Kilner et al. 2002; Mayston et al. 2001).

There is some evidence that the two measures of correlated motor-unit discharge provide different information about the activation of spinal motor neurons. For example, a model by Kirkwood and Sears (1978, 1991) predicted a narrow peak in the cross-correlation histogram by equations that assumed monosynaptic excitatory postsynaptic potentials (EPSPs) even in the absence of rhythmic patterns in the synaptic inputs. In addition, the application of transcranial magnetic stimulation of the motor cortex enhanced coherence in the 16- to 32-Hz band but did not influence the cross-correlation histogram for motor units in the first dorsal interosseus muscle (Mills and Schubert 1995). Nonetheless, some observations suggest that the coherence spectrum may contain information about motor-unit synchronization. For example, both the amount of motor-unit synchronization and the amplitude of the 16- to 32-Hz band in the coherence spectrum were greatly reduced in stroke patients compared with healthy adults (Farmer et al. 1993a, 1997). Furthermore, both young and old adults exhibited similar motor-unit synchronization and 16- to 32-Hz coherence when performing isometric contractions with the first dorsal interosseus muscle, despite the older adults having greater coherence at frequencies < 10 Hz (Semmler et al. 2000, 2003).

One possible explanation for these experimental findings is that the two measures of correlated discharge are complementary to each other with the cross-correlation histogram indicating motor-unit synchronization due to either branched common input or presynaptic cortical synchrony and the coherence analysis denoting common oscillations in descending drive. Alternatively, rhythmic synaptic input to the spinal motor neurons may produce both motor-unit synchronization and peaks in the 16- to 32-Hz band of the coherence spectrum. The purpose of this study was to determine the influence of motor-unit synchronization on the cross-correlation histogram and coherence spectrum for pairs of simulated motor units. The results indicated that motor-unit synchronization can influence both the cross-correlation histogram and the coherence spectrum, independent of commonly modulated descending inputs. Some of these data have been presented in abstract form (Moritz et al. 2004).

METHODS

A model of recruitment and rate coding implemented in Python 2.3 software was used to generate discharge times for a pool of 120 motor

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units (Fuglevand et al. 1993; Taylor et al. 2002, 2003; Yao et al. 2000). The parameters of the model were set to approximate the physiological properties of an intrinsic hand muscle, the first dorsal interosseus (Enoka and Fuglevand 2001). Briefly, the motor-unit twitch forces ranged from 1 to 100 arbitrary units and were exponentially distributed across the pool. Twitch time was inversely proportional to twitch force, decreasing from 90 to 30 ms across the population. Motor units were activated when the excitation level exceeded an exponential recruitment function. All motor units began discharging action potentials at 8 pulses per second (pps). Discharge rate increased linearly with excitation until the peak value was reached, and then discharge rate was held constant as excitation continued to increase. Peak discharge rate decreased across the population from 35 pps for *motor unit 1* to 25 pps for *motor unit 120*. Variability in discharge rate was produced by randomly varying discharge times with a coefficient of variation (CV) of 20%. Table 1 summarizes the number of active motor units, mean discharge rate, and CV of discharge rate for the six simulated forces.

Each trial consisted of a 1-s ramp in the excitation function from zero to a value that produced the target force, followed by a 119-s contraction. Whole-muscle force was calculated as the linear sum of the motor-unit forces, which were scaled by a gain function when the twitches began to fuse (Fuglevand et al. 1993). Maximal force (MVC) was equal to the force produced at 100% excitation, and all forces are reported as a percent of the MVC value.

Motor-unit synchronization was simulated by aligning individual discharge times from separate motor units (Taylor et al. 2002, 2003; Yao et al. 2000). This process was intended to represent the effect of branched common input, excitatory or inhibitory, causing the discharge of one motor unit to be advanced or delayed so that it occurred nearly simultaneously with the discharge of another motor unit. The discharge times that were aligned were selected randomly, but a 30-ms limit was placed on the maximal time that discharges could be advanced or delayed to approximate physiological adjustments (Matthews 2002).

The percent synchrony was varied from 0 to 40%, which defined the proportion of the discharges by each motor unit that served as a reference to which discharge times from other units were aligned. After a discharge by the reference unit was randomly selected, another motor unit with a similar recruitment threshold was randomly chosen using a Gaussian distribution with a SD of 15 units, but within the range of ± 45 units (threshold based synchrony) (see Datta and Stephens 1990; Huesler et al. 2000; Schmied et al. 1994). If a discharge time for this motor unit occurred within ± 30 ms of the discharge by the reference unit ("adjustment time limit"), this discharge time was aligned with the reference unit with a Gaussian distribution that had a SD of 1.67 ms centered on the reference unit. This process was repeated until the discharge times for six other motor units were aligned with the reference unit; this kept the amount of motor-unit synchronization constant across the pool of motor units. Subsequently, the process was repeated for the next discharge of the reference motor unit, ad seriatim for all motor units in the pool.

TABLE 1. *Motor-unit discharge characteristics in the absence of correlated discharges*

Force (% MVC)	2.5%	5%	15%	30%	45%	60%
Number of MUs active (of 120)	48	65	92	109	118	120
Mean discharge rate, pps	9.6	11.5	15.3	19.3	22.4	27.5
CV of discharge rate, %	23.0	22.7	22.3	22.4	22.5	22.5
CV of discharge rate, pps	2.21	2.61	3.41	4.32	5.04	6.19

Mean discharge rate and coefficient of variation (CV) of discharge rate are for 20 randomly selected motor units in each condition. CV of discharge rate in pulses per second (pps) was calculated by multiplying the CV for discharge rate in percent by the mean discharge rate to provide an estimate of discharge rate variability in units of frequency. MU, motor unit.

Because each motor unit served as a reference, the discharge times for all motor units in the pool were adjusted. In rare cases, the alignment of a discharge resulted in an interspike interval of <20 ms for consecutive discharges by the same motor unit. When this occurred, the interspike interval was increased to 21 ms to avoid the mechanical consequences of a double discharge. The actual adjustment times used in each simulation were uniformly distributed between -30 and 30 ms because discharges were originally random (Fig. 1). The mean absolute adjustment time was 14 ms, and the discharge rate variability produced by these adjustments was within physiological limits (Table 2).

In a subset of simulations, the adjustment time limit was varied from 10 to 60 ms to examine its effect on coherence peak frequency. In all conditions, the distribution of adjustment times ended abruptly at the time limit (see Fig. 1). Similar coherence spectra, however, were produced by conditions where the adjustment-time distribution decayed exponentially to zero. The abrupt end to the adjustment-time distribution was chosen to eliminate the nonphysiologically large adjustment times near the tail of an exponential relation (see Yao et al. 2000).

The simulations involved individual combinations of muscle force and motor-unit synchronization: muscle force was set to six levels: 2.5, 5, 15, 30, 45, and 60% MVC and motor-unit synchronization was set to five levels: 0, 5, 12, 22, and 40%. The effects of these conditions on the discharge times of sample motor units are shown in Fig. 2.

At each simulated force, 20 pairs of motor units were randomly selected to be included in the analysis to approximate the sampling that occurs during experimental measurements. First, a reference unit was selected from the pool with a linear probability of selection. Motor units with recruitment thresholds near the extremes of the pool were not used as reference units, which excluded units with recruitment thresholds less than *motor unit 15* and those within 15 of the last recruited unit at a given force level. To complete the pair, a second motor unit was then selected using a Gaussian probability with a SD of 15 units that was centered on the reference unit. This process was repeated until 20 motor-unit pairs were selected, and no motor unit was included in more than one pair. The same motor-unit pairs were used in the analysis of all conditions at a given simulated force.

The time-domain measures of motor-unit synchrony that were calculated for each condition included common input strength (index CIS), index E, index k' (Nordstrom et al. 1992), and the population synchrony index (PSI; Yao et al. 2000). For each motor-unit pair, a cross-correlation histogram was constructed by comparing each discharge time by the reference motor unit with all discharge times by the other unit within ± 100 ms. Inflections in the cumulative sum of the histogram defined the width of the central peak (Ellaway 1978) and the number of counts in the central peak above those due to chance was calculated (P). Index CIS (pps) was calculated as the ratio of P to the duration of the data analyzed (2 min in the current simulations) (Nordstrom et al. 1992). Index E (pulses/trigger) corresponded to the ratio of P to the total number of discharges by the reference unit (Datta and Stephens 1990; Datta et al. 1991). Index k' denoted the ratio that was determined from the sum of P divided by the number of counts in the peak region below those due to chance (C), divided by C (Ellaway and Murthy 1985; Nordstrom et al. 1990). Finally, the PSI was calculated to provide a measure of the number of coincidental discharge times in excess of that expected due to chance for independent activation of the population of motor units (Yao et al. 2000).

Correlations in the frequency domain were examined with the coherence spectrum (Rosenberg et al. 1989). Briefly, discharge times from each pair of motor units were partitioned into contiguous, nonoverlapping epochs of 1.28 s that each comprised 256 bins. Each 5-ms bin was then given a value of 1 when it contained a discharge time and a value of 0 when it did not. These time-series data were then transformed into the frequency domain with a resolution of 0.78 Hz. Auto- and cross-spectra were estimated, and a coherence estimate was computed. Subsequently, 95% confidence intervals (CIs) above both zero and the mean value over the entire coherence spectrum were computed to identify significant peaks. Two frequency bands were

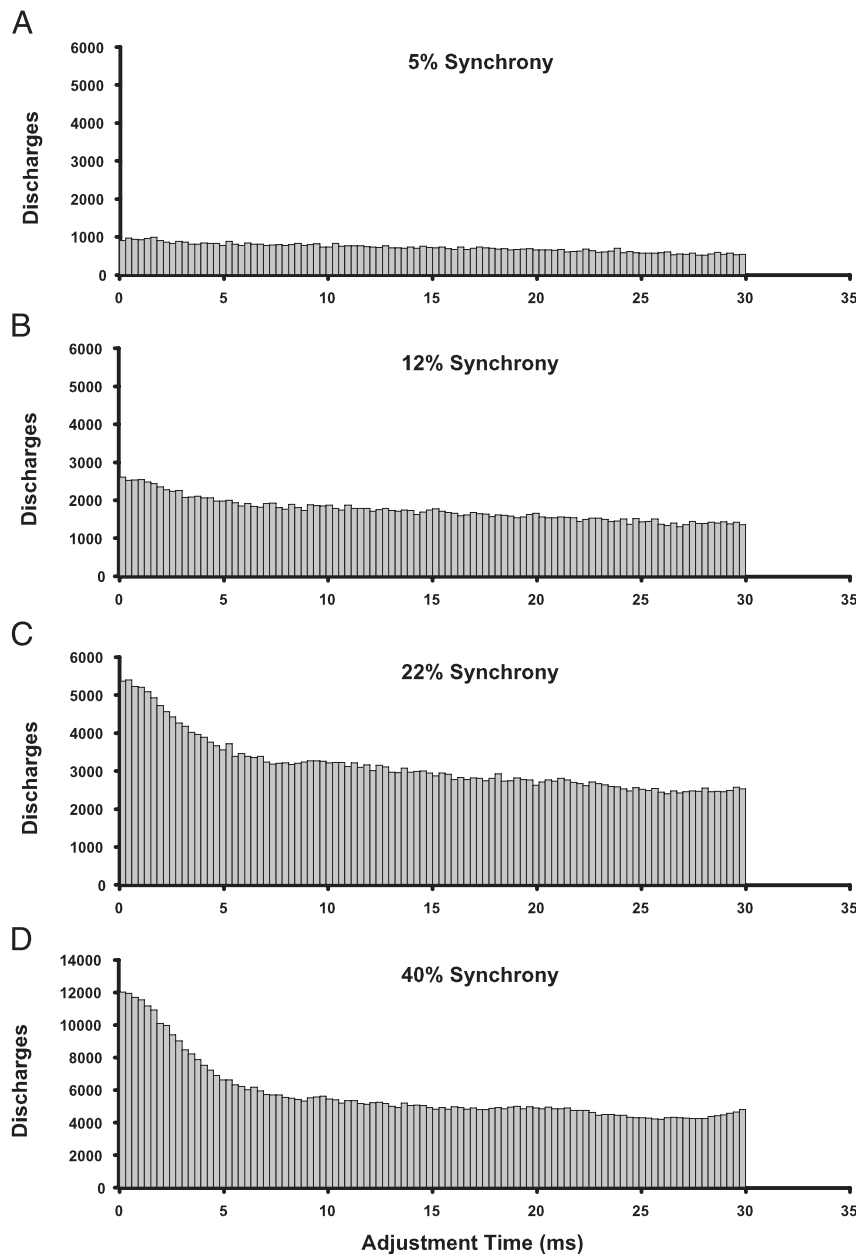


FIG. 1. Histograms of the adjustment times imposed on all the motor-unit discharges during a 30% maximal force (MVC) at 4 levels of motor-unit synchronization: 5% (A), 12% (B), 22% (C), and 40% (D). The discharge times were randomly selected for adjustment, and therefore the adjustment times were nominally uniformly distributed between 0 and the maximal adjustment time (30 ms). At higher levels of synchrony (B–D), slightly more discharges were adjusted by brief intervals because the recursive process of imposing synchrony caused the discharge times to cluster around common times.

analyzed in the coherence spectrum: 0–5 and 16–32 Hz. For each frequency band, a peak value was determined when the coherence exceeded the 95% CI above zero. In addition, the integrated area of coherence for the band was calculated above the 95% CI. When coherence did not exceed the 95% CI, a value of zero was recorded.

The number of motor-unit pairs needed to obtain stable time- and frequency-domain measures of synchrony was also examined. The mean of progressively greater numbers of motor-unit pairs was computed for each condition and for the following measures: indexes CIS, E, k' , and the size of the 16- to 32-Hz band in the coherence spectrum. A sufficient number of motor-unit pairs corresponded to the fewest number of pairs with a mean that fell within 1 SD of the mean of all 20 pairs. Subsequently, the order of the motor-unit pairs was randomly shuffled 10 times, and the progressive means and sufficient number of pairs was recalculated each time to obtain an average of the sufficient number of motor-unit pairs. Mean values for indexes CIS, E, and k' stabilized after no more than five, but normally two, randomly ordered motor-unit pairs (Table 3). Similarly, the peak and area in the

16- to 32-Hz band of the coherence spectrum stabilized after two independently tested motor units (Table 3).

The interval over which selected discharge times could be moved to impose motor-unit synchronization was varied in a subset of simulations to examine its effect on the coherence spectrum. Maximal adjustment times of 30, 15, and 10 ms were compared. For each adjustment time, a cross-correlation histogram was constructed and smoothed using a 50-Hz low-pass filter. Subsequently, the peak-to-shoulder interval in the smoothed histogram was determined, and the inverse was calculated to predict the peak frequency in the coherence spectrum.

Statistics

Twenty motor-unit pairs were randomly selected from each condition to provide sampling variability. The dependent variables in the time domain were the indexes CIS, E, and k' . The dependent variables in the frequency domain were the amplitudes of the peak and the area

TABLE 2. Discharge rate, variability, and peak width across levels of motor-unit synchronization and force

Synchrony (% imposed)	0%	5%	12%	22%	40%
2.5% MVC					
ISI, ms	109.3 ± 7.1	109.4 ± 7.1	109.2 ± 7	109.1 ± 6.4	109.4 ± 7.3
SD of ISI, ms	21.8 ± 1.8	25.2 ± 1.1	29.0 ± 1	32.9 ± 1	36.0 ± 0.9
Peak width, ms	8.0 ± 4.1	7.9 ± 2.3	9.5 ± 1.8	10.1 ± 1.4	10.7 ± 1.5
5% MVC					
ISI, ms	91.5 ± 5.6	91.5 ± 5.5	91.3 ± 5.4	91.5 ± 5.4	91.2 ± 4.9
SD of ISI, ms	18.1 ± 1.2	22.5 ± 0.9	26.9 ± 1	31.0 ± 1.2	34.3 ± 1
Peak width, ms	6.9 ± 3.6	8.7 ± 3.2	9.5 ± 1.9	10.4 ± 1.8	11.4 ± 1.7
15% MVC					
ISI, ms	69.1 ± 9.0	69.0 ± 8.8	69.1 ± 8.8	69.2 ± 9	68.9 ± 8.6
SD of ISI, ms	13.6 ± 1.7	18.3 ± 1.6	22.4 ± 1.9	26.1 ± 2.3	28.8 ± 2.4
Peak width, ms	7.6 ± 4	7.6 ± 4.4	9.2 ± 1.4	11.0 ± 1.8	11.2 ± 1.5
30% MVC					
ISI, ms	55.7 ± 9.7	55.6 ± 9.7	55.6 ± 9.6	55.5 ± 9.6	55.6 ± 9.8
SD of ISI, ms	11.0 ± 1.9	15.5 ± 2.3	18.9 ± 2.8	21.6 ± 3.5	23.8 ± 3.7
Peak width, ms	7.0 ± 4.2	6.6 ± 3.1	8.1 ± 2.1	9.7 ± 2.2	10.2 ± 1.6
45% MVC					
ISI, ms	47.9 ± 8.5	48.0 ± 8.7	47.9 ± 8.6	48.0 ± 8.6	47.9 ± 8.6
SD of ISI, ms	9.4 ± 1.7	13.5 ± 2.2	16.5 ± 3	18.5 ± 3.5	20.4 ± 4
Peak width, ms	8.0 ± 3.6	6.1 ± 2.6	8.5 ± 3.6	9.0 ± 2.3	9.5 ± 2.8
60% MVC					
ISI, ms	38.9 ± 6.6	38.9 ± 6.5	38.9 ± 6.6	38.9 ± 6.5	39.0 ± 6.7
SD of ISI, ms	7.7 ± 1.3	10.9 ± 2	13.1 ± 2.6	14.6 ± 3	15.8 ± 3.5
Peak width, ms	9.3 ± 3.7	6.5 ± 4.1	6.1 ± 2	7.8 ± 2.8	8.4 ± 2.3

Means ± SD for interspike interval (ISI), the standard deviation of interspike interval, and the width of the peak in the cross-correlation histogram for 20 randomly selected motor units at each force level.

in the 0- to 5-Hz and 16- to 32-Hz bands of the coherence spectrum. Each dependent variable was analyzed with a mixed, two-factor ANOVA (5 synchronization levels × 6 excitation levels) with repeated measures on synchronization. The excitation level was considered as a between-subject variable because different pairs of motor units were included in each of the six levels. Bivariate correlations were used to examine the relation between 1) imposed synchrony and time-domain measures (indexes CIS, E, and k'); 2) imposed synchrony and peak in the 0- to 5- and 16- to 32-Hz bands in the coherence spectrum; and 3) time-domain measures (indexes CIS, E, and k') and peaks in the 0- to 5-Hz and 16- to 32-Hz bands of the coherence spectrum. The alpha level for all statistical tests (SPSS 11.5) was set at 0.05, and all significant interactions were followed with appropriate post hoc analyses, for example, one-way ANOVAs with Bonferroni corrections for differences between the level of imposed synchronization. Confidence levels were set at 95% for the coherence analysis.

RESULTS

The results of the study characterized the ability of the cross-correlation histogram and the coherence spectrum to detect motor-unit synchronization that was imposed on the discharge times of simulated motor units.

Motor-unit synchronization

All three time-domain measures of synchrony (indexes CIS, E, and k') increased ($P < 0.01$) with the imposed level of motor-unit synchronization (Fig. 3). There was an interaction, however, between the influence of motor-unit synchronization and the amplitude of the simulated force ($P < 0.01$). The effect on index CIS, which is most evident at 40% imposed synchrony (Fig. 3A), was a nonmonotonic change in its amplitude with an increase in force. For example, index CIS was greatest at 15% MVC force, intermediate at 2.5% MVC force and least

at 60% MVC force, which indicates the effect of force on the proportion of discharge times that were aligned with a reference motor unit. In contrast, indexes E and k' both declined monotonically with an increase in force as did the number of normalized coincidental discharge times (PSI; Fig. 3D). This effect was due to an increase in the number of discharges required to increase force (Table 1), which increased the denominator for the two indexes E and k' but not index CIS. The width of the peak in the cross-correlation histogram increased with greater amounts of synchrony ($P < 0.001$) and decreased slightly at high forces compared with low forces ($P = 0.025$; Table 2).

Motor-unit synchronization produced a peak in the 16- to 32-Hz band of the coherence spectrum (Fig. 4H), and the amplitude of the peak was associated with the amount of imposed motor-unit synchronization (Fig. 5). Motor-unit synchronization had a significant ($P < 0.01$) influence on both the magnitude and the area of the peak in the 16- to 32-Hz band (Fig. 5, B and D), but not the size of the peak in the 0- to 5-Hz band (Fig. 5, A and C). Similar to the time-domain measures, both the magnitude and the area of the peak in 16- to 32-Hz band of the coherence spectrum decreased as the simulated force increased.

Time-domain measures of motor-unit synchronization were highly correlated with the magnitude of the peak in the 16- to 32-Hz band of the coherence spectrum (Fig. 6). Across all levels of synchrony and contraction force, the magnitude of the peak in the 16- to 32-Hz band was strongly correlated with the three indexes (r^2 values > 0.80 ; Fig. 6, B, D, and F). The relation between the magnitude of the 16- to 32-Hz peak and the time-domain measures was described by a second-order polynomial, and the highest correlation ($r^2 = 0.98$) was for index E. Similarly, the area of the peak in the 16- to 32-Hz band

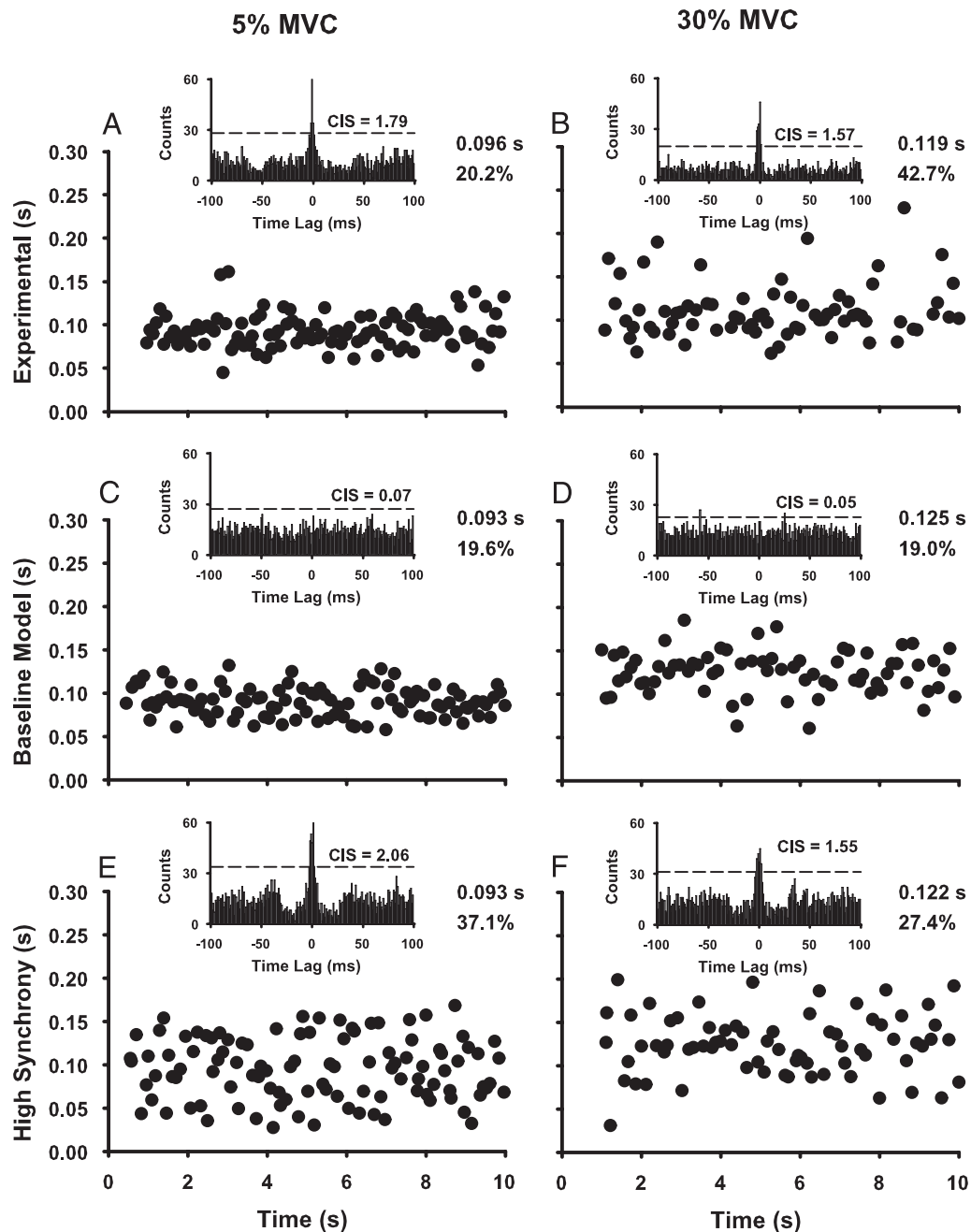


FIG. 2. Interspike intervals (ISI) for experimental data and 2 model conditions. *Left*: data for motor units that were recruited slightly below the target force of 5% MVC. *Right*: similar data for motor units recruited slightly below the target force of 30% MVC. The mean ISI and its coefficient of variation are indicated in the top right-hand corner of each panel. *A* and *B*: experimental data for motor units in first dorsal interosseus during isometric contractions. *C* and *D*: model data with 20% coefficient of variation for discharge rate and no motor-unit synchronization. *E* and *F*: model data for 40% imposed motor-unit synchronization. *Insets*: cross-correlation histograms derived from the discharge times of the example motor unit and another motor unit with a similar recruitment threshold. ---, 95% confidence intervals.

was highly correlated with all time-domain measures (r^2 values > 0.74). The associations between the three indexes and the peak in the 0- to 5-Hz band were not significant ($r^2 \leq 0.05$; Fig. 6, *A*, *C*, and *E*).

The coherence peak in the 16- to 32-Hz band was influenced by the time interval over which discharges were moved to impose motor-unit synchronization. This interval, termed the adjustment time limit, was 30 ms in the present model, which meant that randomly selected discharge times within 30 ms of a reference discharge time could be aligned with

the reference discharge to produce synchrony. When this adjustment time was varied, the peak in the coherence spectrum changed predictably due to the relation between the period of the cross-correlation histogram and the peak frequency in the coherence (Fig. 7). This association is shown by the smooth curves and vertical lines to denote the approximate period of each adjustment-time condition (Fig. 7, *A–C*). Peaks in the coherence spectrum occurred at the frequency predicted by the histogram period in all cases (Fig. 7, *D–F*).

TABLE 3. Number of motor-unit pairs needed for a reliable estimate of motor-unit synchronization

Synchrony (% imposed)	0%	5%	12%	22%	40%
Index CIS	1.39 ± 0.27	1.57 ± 0.41	1.59 ± 0.23	1.59 ± 0.33	1.46 ± 0.30
Index E	1.50 ± 0.25	1.79 ± 0.16	1.60 ± 0.38	1.56 ± 0.55	1.64 ± 0.42
Index k'	1.61 ± 0.36	1.84 ± 0.39	1.31 ± 0.17	1.46 ± 0.32	1.46 ± 0.19
Coherence					
Peak 16–32 Hz	—	—	—	1.28 ± 0.48	1.61 ± 0.54
Area 16–32 Hz	—	—	—	1.60 ± 0.57	1.92 ± 0.59

Means ± SD for 10 randomly ordered pairs of 20 motor units. Because of the absence of a main effect for force, all forces are grouped for each level of synchrony.

Discharges were aligned with various amounts of jitter to examine the effects of narrow- and broad-peak synchrony on the coherence spectra (Fig. 8). Although the magnitude of synchrony and coherence decreased ($P < 0.001$) as the width of the peak increased from 4.8 to 12.0 ms, the frequency of the coherence peak did not change ($P = 0.360$).

DISCUSSION

The main finding of this study was that peaks in the cross-correlation histogram and in the 16- to 32-Hz band of the coherence spectrum can be caused by motor-unit synchronization imposed with a maximal adjustment time of 30 ms. Furthermore, the frequencies at which the peaks occurred in the coherence spectrum were directly related to the adjustment times used to impose motor-unit synchronization.

The process of advancing or delaying individual discharge times to align pairs of motor-unit action potentials imposed a frequency structure on the discharge times that appeared in the coherence spectrum. The effect of the times over which discharges were moved (i.e., “adjustment time”) on the coherence frequency is apparent in Fig. 7. The choice of maximal adjustment time was based on the physiological estimates of the time that postsynaptic potentials can advance or delay the generation of an action potential. With a maximal adjustment time of 30 ms, discharge times were moved an average of 14 ms, and physiological values for discharge rate variability were produced (Mori 1973; Person and Kudina 1972; Powers and Binder 2000). This adjustment time is well within the “extreme” limits of ±50 ms proposed by Matthews (2002). In addition, the process of imposing short-term synchrony also resulted in sculpting of the cross-correlation histograms with troughs surrounding the central peak as frequently observed in experimental records (Bremner et al. 1991; Farmer et al. 1993a; Semmler et al. 2000). Even when no limit was placed on the adjustment time, a frequency content was still introduced (equal to half the mean discharge rate), and sculpting of the cross-correlation histogram does occur (see Fig. 3 in Yao et al. 2000).

Physiological interpretation

The findings of the current study indicate that common oscillations may not be required to produce short-term synchrony and coherence at 16–32 Hz. Branched common input may be sufficient to produce both measures of correlated activity by creating either EPSPs that are large enough to cause one or both of the neurons to reach threshold and discharge early or an inhibitory postsynaptic potential that is large enough to delay the discharge of one or both neurons. Further-

more, these bursts of branched common input activity could arrive at random intervals that are less than the discharge rate of the neurons. For example, the branched common input need only burst an average of one in five discharges to produce 20% synchrony (CIS index ~ 1.5) in our model. At an average discharge rate of 10 pps, for example, the branched common input need only occur at an average frequency of 2 pps. In addition, the common bursts may not arrive at regular intervals. Instead of creating ~2 Hz coherence as predicted by the average branched common input rate, imposed synchrony in the present study created coherence peaks in the 16- to 32-Hz range, as predicted by the adjustment time limit.

Synchrony can be produced by both branched common input near the motor neurons or by independent inputs that are synchronized at a presynaptic level in the motor cortex (Farmer et al. 1997; Schmied et al. 1994). For example, efferent neurons in the motor cortex are often synchronized (Baker et al. 2001; Smith and Fetz 1989), and this may result in broad-peak synchrony of motor units due to the greater number of interposed synapses. Nonetheless, the present findings demonstrate that both narrow- and broad-peak synchrony produce peaks in the coherence spectrum between 16 and 32 Hz. In the current context, therefore, common input is used to denote both branched common input of last order interneurons and presynaptic common input at the level of the cortex.

Comparison with experimental data

To facilitate comparison of the simulated motor-unit data with experimental measurements, data were averaged for 20 motor-unit pairs for each condition. Table 1 indicates that mean discharge rate increased from 9.60 pps at 2.5% MVC force to 27.5 pps at 60% MVC force and the CV for discharge rate remained at ~22% across all forces. For comparison, Nordstrom et al. (1992) reported mean discharge rates of motor units in first dorsal interosseus during low-force contractions to range from 6.1 to 17.4 pps and CV for discharge rate to average 19% with a range of 8.3–53.7%. Furthermore, Kamen and Roy (2000) reported average discharge rates of ~25 pps for motor units in first dorsal interosseus during high-force contractions.

The values obtained for the three cross-correlation indexes during the simulations are consistent with the ranges observed experimentally. For example, experimental measurements indicate that index CIS can peak at ~2.0 during low-force contractions with first dorsal interosseus (Mills and Schubert 1995; Nordstrom et al. 1992; Semmler et al. 2002) and apparently reach 5.0, with average values of ~3.0, during high-force contractions performed by young adults with the same muscle (Kamen and Roy 2000). Similarly, maximal values for index E can reach about 0.3 during low-force contractions by first

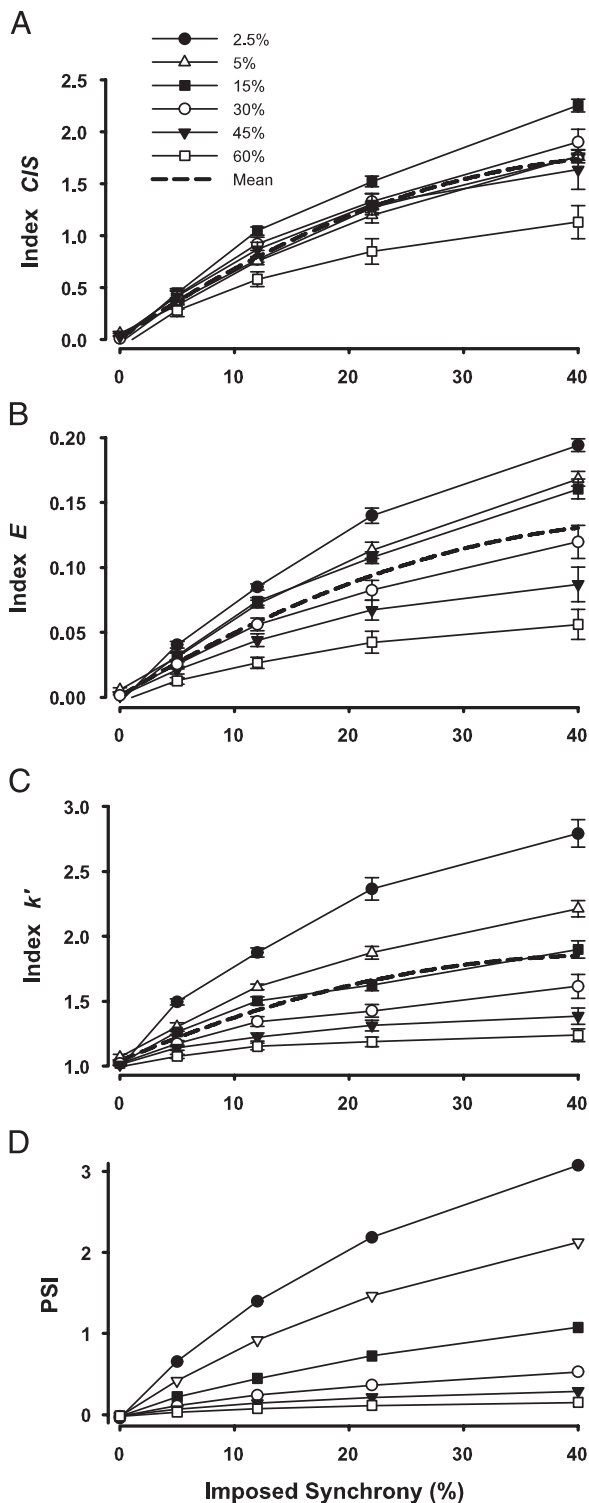


FIG. 3. Influence of imposed motor-unit synchronization and contraction force on the common input strength index (CIS), indexes E and k' , and the population synchrony index (PSI). Synchrony was imposed by aligning 0, 5, 12, 22, or 40% of the times at which the reference motor unit discharged action potentials with the discharge times of 6 other motor units. Values for indexes CIS, E, and k' are means \pm SE for 20 motor-unit pairs that were selected randomly from the population, with the thick dashed lines indicating a 2nd-order regression line for the means of all forces ($r^2 > 0.99$). Values for the PSI (D) indicate the number of coincidental discharge times for all active motor units in excess of those expected due to independent activation of the motor units.

dorsal interosseus (Datta and Stephens 1990; Mills and Schubert 1995; Nordstrom et al. 1992; Semmler et al. 2002) and those for index k' during similar conditions achieve a value of ~ 2.4 (Nordstrom et al. 1992). Furthermore, peak coherence in the 16- to 32-Hz band between the discharge times of motor-unit pairs during low-force isometric contractions with first dorsal interosseus can attain values of ~ 0.1 (Farmer et al. 1993b; Halliday et al. 1999). However, coherence in this band can be weak and depend on the task being performed (Kakuda et al. 1999; Semmler et al. 2002, 2003).

Coherence at 16–32 Hz

Several studies report an association between peaks in the 16- to 32-Hz band of the coherence spectrum and in the cross-correlation histogram or cross-intensity function (Farmer et al. 1993a; Kilner et al. 2002; Rosenberg et al. 1989). For example, recordings from the first dorsal interosseus muscle produced peaks in both the cross-intensity function and the 16- to 32-Hz coherence, whereas recordings from biceps brachii exhibited no peaks in either measure (Farmer et al. 1993a). Similarly, peaks in both the cross-intensity function and the 16- to 32-Hz band of the coherence spectrum were observed in the first dorsal interosseus muscles of healthy and deafferented humans, but not in patients after a stroke, (Farmer et al. 1993a, 1997) and cross-correlation peaks and coherence in the 16- to 32-Hz band both increased when object compliance was reduced when performing a precision grip task (Kilner et al. 2002). Furthermore, Semmler and colleagues found no difference between young and old adults in index CIS (Semmler et al. 2000) or coherence at 16–32 Hz (Semmler et al. 2003), despite reporting a difference between the two groups in coherence at low and high frequencies. Additionally, Halliday et al. (1999) observed a reduction in coherence at 16–32 Hz and a parallel decline in the amplitude of the cumulant density function (an inverse Fourier transform of the cross-spectra) when a muscle was loaded, consistent with a prior report that coherence < 10 Hz is independent of the cumulant density function (Amjad et al. 1997). These associations suggest that both the time- and frequency-domain measures are influenced by the physiological mechanisms that produce motor-unit synchronization.

The simulations performed in the current study support the interpretation of the experimental observations that motor-unit synchronization can influence the size of the peak in the 16- to 32-Hz band of the coherence spectrum. The location of the peak frequencies in the coherence spectrum depends on the intervals over which the discharge times are displaced to produce motor-unit synchronization (see also Davey et al. 1993). Adjusting discharge times to produce synchrony resulted in a central peak surrounded by minima in the cross-correlation histogram (see Fig. 7). The period of the resulting cross-correlation histogram dictates the peak frequency in the coherence spectrum (Halliday and Rosenberg 1999; Halliday et al. 1995; Priestley 1981). Varying the adjustment time over which discharges were moved influenced the period of the cross-correlation histogram and thus the frequency of the peak in the coherence spectrum (see Fig. 7). It should be noted that the cross-correlation histogram was calculated independently from the cross-spectra used to construct the coherence estimates.

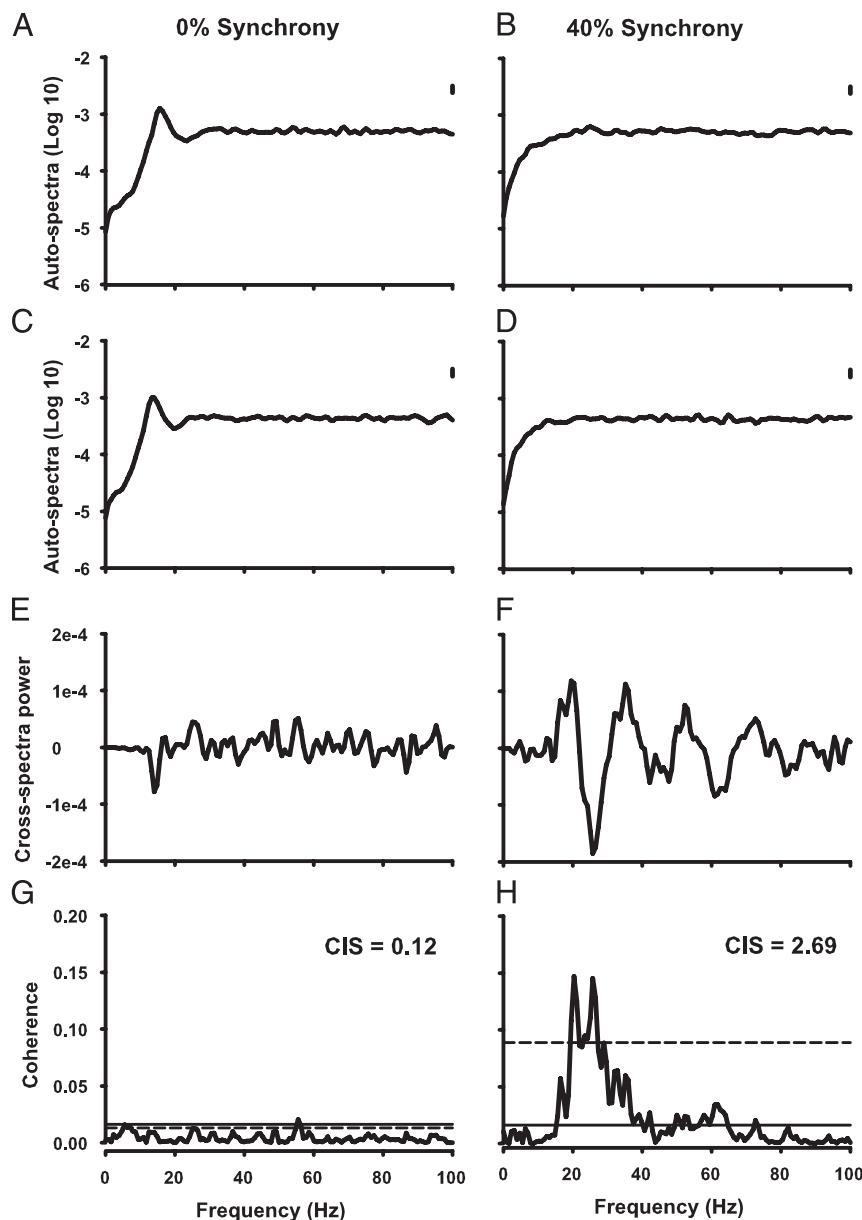


FIG. 4. Sample spectra for 0 and 40% levels of imposed motor-unit synchronization during a 30% MVC contraction. The panels indicate auto power spectra of motor unit 81 (A and B) and motor unit 91 (C and D), cross-spectra (E and F), and coherence spectra (G and H) for motor units 81 and 91. Auto-spectra (A–D) are plotted on a log 10 scale and error bars in the top right-hand corner represent confidence intervals (0.125 for all spectra). At 0% synchrony, peaks in the auto-spectra correspond to the mean discharge rate of the motor units and there were no peaks in the cross- or coherence spectra. At 40% synchrony, mean discharge rate peaks in the auto-spectra are diminished due to alignment of discharge times to produce synchrony, and peaks are evident in the cross- and coherence spectra. — and - - - in the coherence spectra denote 95% confidence intervals >0 and the mean coherence, respectively.

Experimental findings suggest that central oscillations may cause both motor-unit synchronization and peaks in the 16- to 32-Hz band of the coherence spectrum. Evidence for these oscillations is observed as the rippling of the cumulative sum of the cross-correlation histogram or cross intensity function at regular intervals (Farmer et al. 1997; Kilner et al. 2002). Many experimental cross-correlation histograms, however, do not show rippling despite high levels of synchrony (Nordstrom et al. 1992; Semmler et al. 2000) and 16- to 32-Hz coherence (Semmler et al. 2003). Moreover, common input arising from the cortex typically results in broad-peak synchrony due to the greater number of synapses between the source and the muscle (reviewed in McAuley and Marsden 2000). The present results show that both broad- and narrow-peak synchrony can be produced without cortical oscillations, and that both types of synchrony produce coherence in the 16- to 32-Hz band (see Fig. 8).

There is substantial evidence for a cortical origin of the 16- to 32-Hz rhythms that appear in rectified EMG signals. For

example, cortical magnetoencephalogram (MEG) recordings were coherent at 13–35 Hz with contralateral, but not ipsilateral, surface EMG of a hand muscle (Conway et al. 1995). Only subjects with X-linked Kallmann's syndrome and mirror movements exhibit coherence between the ipsilateral cortex and surface EMG and between bilateral EMG recordings (Farmer et al. 2004; Mayston et al. 2001). Further, the difference in phase between MEG and surface EMG recordings for hand and foot muscles were consistent with the difference in distance between the cortex and the two muscles (Halliday et al. 1998; Salenius et al. 1997). However, the MEG-EMG and EMG-EMG coherence at 15–30 Hz between hand and forearm muscles was present during brief sustained contractions but not during movement (Kilner et al. 1999).

Nonetheless, several recent studies have shown that cortical oscillations in the beta range are not perfectly linked to muscle activity. Cortical oscillations are transmitted with only low fidelity through pyramidal tract neurons, and require a population of neurons to relay cortical oscillations to the periphery

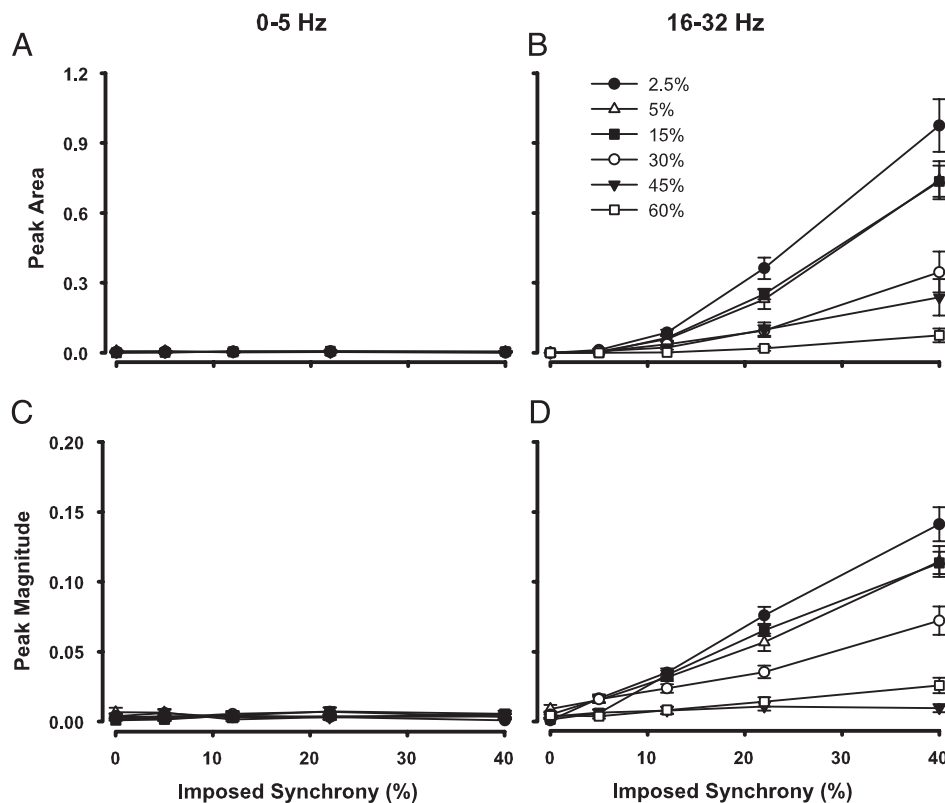


FIG. 5. Area (A and B) and magnitude (C and D) of the peak in the coherence spectra in the 0- to 5-Hz and 16- to 32-Hz frequency bands at 5 levels of imposed motor-unit synchronization and 6 simulated forces. Values are means \pm SE for 20 motor-unit pairs that were selected randomly from the population.

(Baker et al. 2003). Further, EEG-EMG coherence was not influenced by diazepam treatment, despite a doubling of EEG power near 20 Hz (Baker and Baker 2003). This relatively fixed EEG-EMG coherence might be explained by the results of the current study. Perhaps pyramidal tract neurons transmit some amount of beta range cortical oscillations onto spinal interneurons that then branch and synapse on many motor neurons, but the time over which motor neuron discharges can be advanced or delayed by these branched inputs may restrict both the frequency and magnitude of coherence among motor units and between EMG and the cortex. Of course, a separate input to these branched spinal interneurons would be required to adjust the magnitude of synchrony and coherence observed in different tasks (Kilner et al. 2000).

Motor-unit synchronization in the current simulations selectively produced coherence peaks in the 16- to 32-Hz frequency band but not the 0- to 5-Hz band. Experimental records, however, also show peaks in the coherence spectra at 1–5 and 8–10 Hz that are assumed to reflect common low-frequency oscillations or common drive (DeLuca and Erim 2001; Farmer et al. 1993a; Marsden et al. 1999). Because the discharge times in the simulations were initially random, oscillations were not present at lower frequencies, which resulted in the imposed synchrony being isolated in the 16- to 32-Hz band of the coherence spectrum.

Indexes of motor-unit synchronization

All three time-domain measures (indexes CIS, E, and k') and the 16- to 32-Hz coherence resolved differences in the amount of motor-unit synchronization. There were several differences, however, between these measures. For example, time-domain measures exhibited a decreasing slope with

increased synchrony (Fig. 3), whereas coherence measures increased linearly with increased synchrony (Fig. 5). The effect of varying the level of synchrony on the time-domain measures may partly be a consequence of the strategy that was used to impose motor-unit synchronization. Discharge times were adjusted sequentially from the smallest to the largest motor unit, which meant that prior adjustments could themselves be subsequently altered when synchrony was being imposed on larger motor units. As indicated by the PSI (Yao et al. 2000), the PSI did not increase proportionally with the imposed synchrony at high levels of synchrony (Fig. 3D). Therefore the decreasing slope of the relations between the indexes CIS, E, and k' and the level of imposed synchrony was likely a consequence of the method used to impose synchrony in the model and not due to saturation of the indexes at high levels of synchrony. Nonetheless, others have demonstrated that the amplitude of the indexes derived from the cross-correlation histogram do not increase proportionally with the amount of common input (Binder and Powers 2001; Taylor and Enoka 2004).

There were at least two main differences among the three indexes in response to the imposed conditions. First, index CIS changed nonmonotonically with force (Fig. 3). Because index CIS (pps) corresponds to the number of counts in the peak of the cross-correlation histogram relative to the duration of the contraction (2 min in these simulations), the observed change in index CIS must be a consequence of the strategy used to impose motor-unit synchronization. Furthermore, the monotonic decline in the other two indexes (E and k') with force reflects the combined effect of the accumulation of counts in the peak and the increase in average discharge rate with force (Table 1). As indicated by the PSI, the number of coincidental

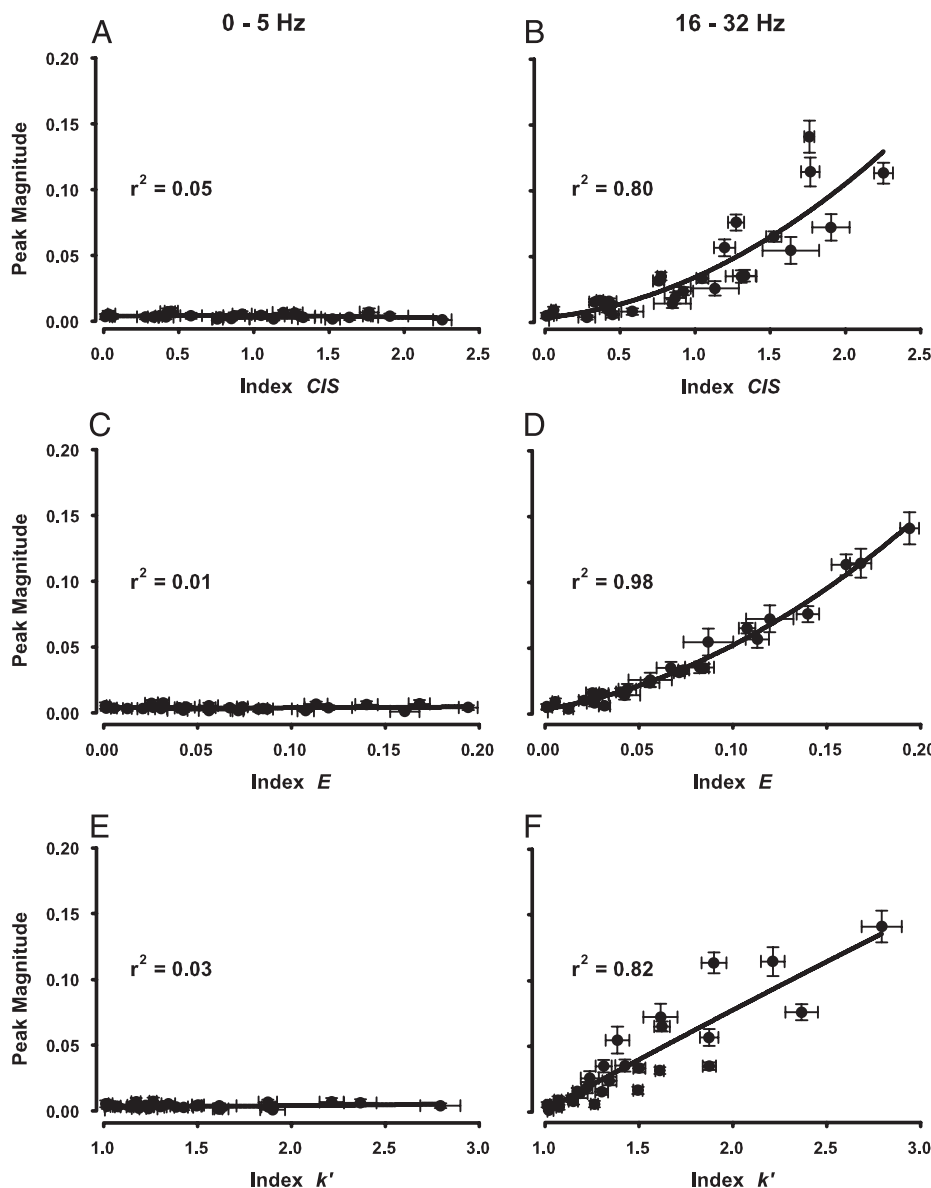


FIG. 6. Correlations between coherence and cross-correlation measures across all levels of motor-unit synchronization. Each data point indicates the magnitude of the peak in one of the 2 bands (0–5 Hz and 16–32 Hz) of the coherence spectrum for a given level of imposed motor-unit synchronization and amplitude of simulated force. Relations are shown for index CIS (A and B), index E (C and D), and index k' (E and F). Values are means \pm SE for 20 motor-unit pairs that were selected randomly from the population. The regression lines are 2nd-order polynomials with equations: A: $-0.0008x^2 + 0.0013x + 0.0037$; B: $0.0201x^2 + 0.0107x + 0.0360$; C: $0.0567x^2 - 0.0083x + 0.0040$; D: $2.5037x^2 + 0.2371x + 0.0035$; E: $0.0008x^2 - 0.0022x - 0.0520$; F: $0.0017x^2 + 0.0814x - 0.0783$.

discharge times declined with an increase in the simulated force (Fig. 3D). Second, index E (pulses/trigger) had the strongest association of the three indexes with peak magnitude in the 16- to 32-Hz band of the coherence spectrum (Fig. 6). This high correlation may be due to the derivation of index E as the number of synchronous discharges divided by the total number of discharges in the record. Because the number of discharges that occur during a finite duration is analogous to the discharge rate, index E is the only time-domain measure that is directly normalized to discharge rate. This normalization to frequency may explain the high correlation between index E and the coherence, a frequency-domain correlation.

The magnitude of synchrony was greatest during low-force contractions ($\leq 15\%$ MVC) and decreased at higher forces. This result is similar to experimental observations of an inverse relation between the amount of motor-unit synchronization and the time to peak force in a twitch response, which was used as an index of recruitment threshold; slow-twitch motor units were more synchronized with one another than fast-twitch

units (Schmied et al. 1993, 1994). Furthermore, the width of the peak in the cross-correlation histogram was modestly related to recruitment threshold in the dominant arm but not the nondominant arm (Schmied et al. 1994). The current simulations produced a small decrease in peak width across the range of simulated forces.

Limitations of the model

Motor-unit synchronization refers to the correlated discharge of action potentials by motor units. It is a consequence of common synaptic input received by motor neurons either from branched last-order interneurons or from cortical efferents that receive common input. The current study approximated these inputs by aligning a proportion of the discharge times for pairs of motor units. The alignment procedure reproduced the level of correlation in the discharge times of motor units that has been observed experimentally, but it provided no insight on the mechanisms that can produce the correlated discharge. The greater-than-chance occurrence of synchronous discharges, for

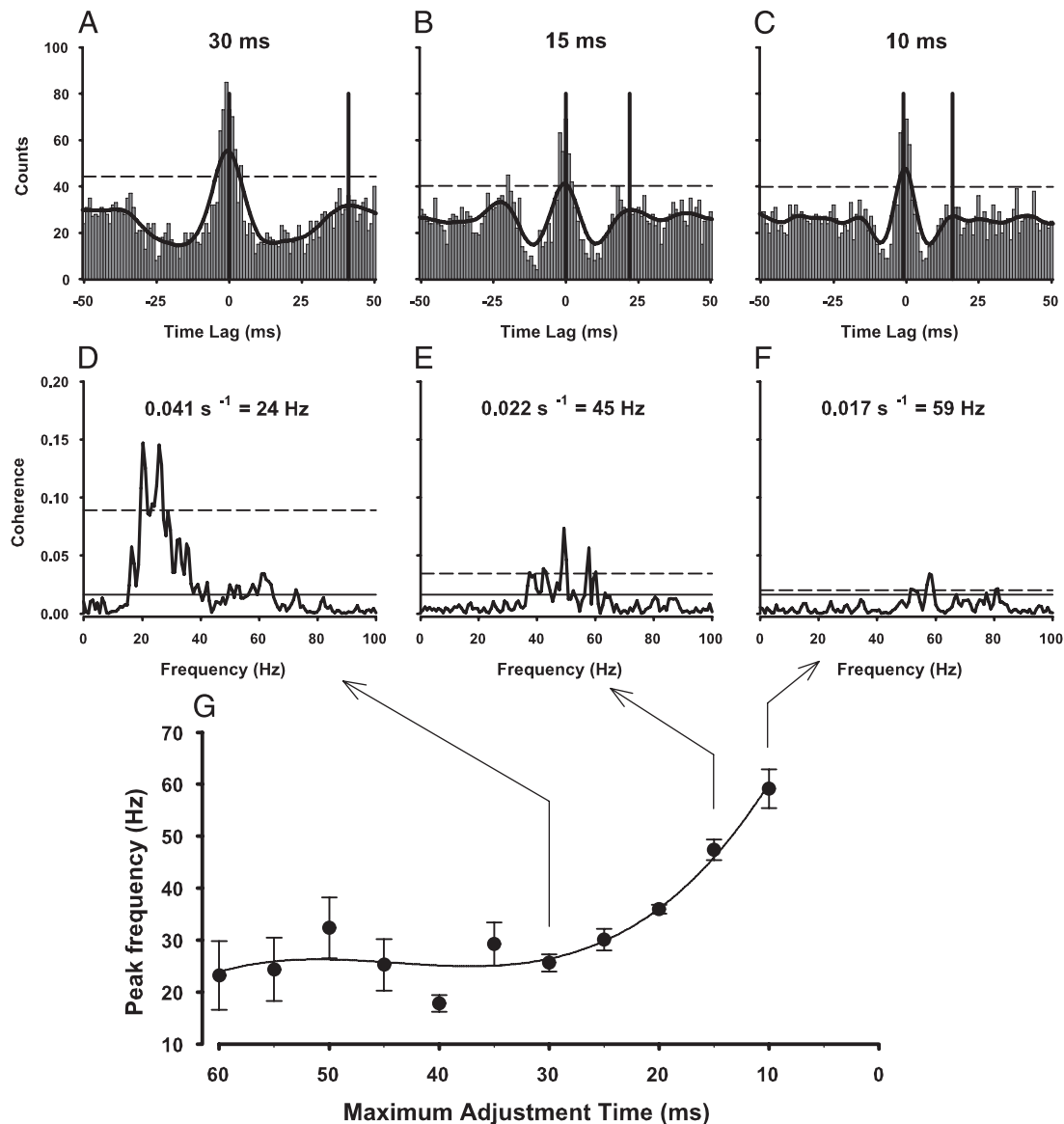


FIG. 7. The location of the peak in the coherence spectrum depended on the range over which discharge times were moved to create the imposed motor-unit synchronization. Representative cross-correlation histograms (A–C) and coherence spectra (D–F) for motor units 81 and 91 with 40% imposed synchrony during a simulated contraction at 30% MVC. Synchrony was imposed by using adjustment limits of 30, 15, and 10 ms. The thick lines on the cross-correlation histograms represent low-pass filtered histograms to produce a smooth curve, and the vertical lines denote the period of each smooth curve that defined the peak frequency in the coherence spectra. Horizontal dashed lines on the cross-correlation histograms denote 95% confidence intervals. Horizontal solid and dashed lines in the coherence spectra denote 95% confidence intervals >0 and the mean coherence, respectively. The amount of imposed synchrony, and hence the magnitude of coherence, decreased with briefer times due to the fewer discharge times that were available for alignment. G: the peak frequency in the coherence spectrum as a function of the adjustment time limit used to impose synchrony during a 30% MVC contraction (mean \pm SE for 20 motor-unit pairs). Coherence peaked at ~ 24 Hz unless adjustment time limits of <20 ms were used.

example, can be produced either by branched common input in the spinal cord or motor cortex, inhibitory circuits, or intrinsic conductances of the motor neurons (Taylor and Enoka 2004). Nonetheless, the purpose of the study was to determine the effect of short-term synchrony on the cross-correlation histogram and the coherence spectrum and not to examine the underlying mechanisms.

The current model did not examine the shape or time course of EPSPs. Previous studies have found that the shape of the peak in the cross-correlation histogram and the maximum coherence that can be detected were influenced by EPSP shape (Farmer et al. 1993a; Kirkwood and Sears 1978). Specifically, EPSP shape acts as a filter on the maximal

coherence, but only at frequencies well above those of interest in the current study (>250 Hz). As the present model only modulated discharge times, coherence frequencies were not created by EPSP shape but rather by imposed short-term synchrony.

A previous simulation study (Taylor and Enoka 2004) found that the indexes of synchronization were greater at higher levels of excitation when the level of common input was constant. In contrast, the present study found that the synchronization indexes were generally lower at higher levels of excitation (see Fig. 3). This difference in the relation between the strength of motor-unit synchronization and simulated force was due to the method used to impose synchrony. In the

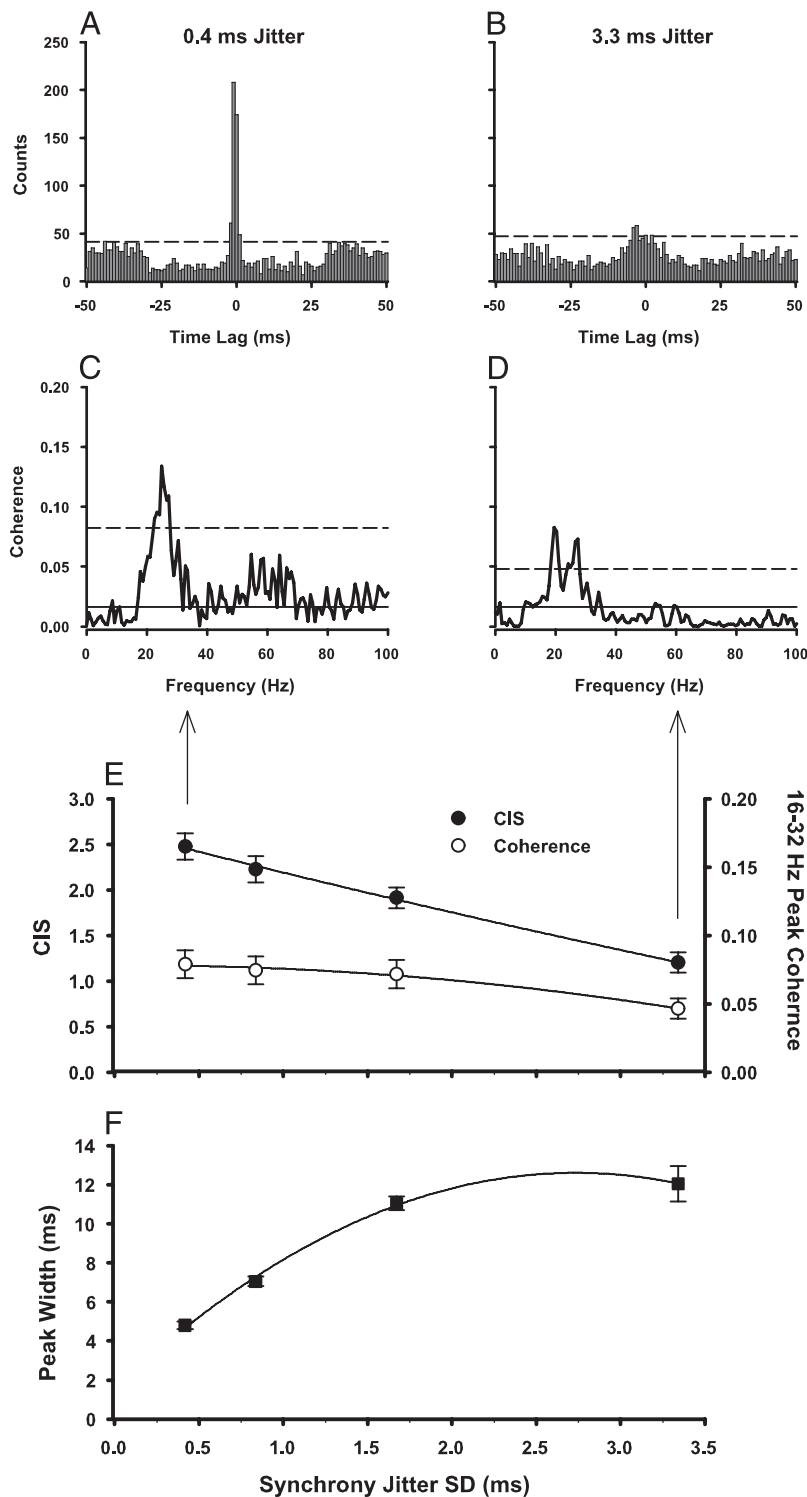


FIG. 8. The influence of jitter in the alignment of the discharge times when synchrony was imposed. Representative cross-correlation histograms (*A* and *B*) and coherence spectra (*C* and *D*) for motor units 81 and 91 with 40% imposed synchrony during a simulated contraction at 30% MVC. *A* and *C* show that a minimal amount of jitter (SD of jitter = 0.4 ms) produced a narrow peak in the cross-correlation histogram. *B* and *D* show that a greater amount of jitter (SD of jitter = 3.3 ms) produced a broad peak in the cross-correlation histogram. An increase in the jitter of the alignment times (means \pm SE for 20 motor-unit pairs) decreased both the CIS index and the amplitude of the 16- to 32-Hz peak in the coherence spectrum (*E*) and increased the width of the peak in the cross-correlation histogram (*F*). Coherence in the 16- to 32-Hz frequency band was sensitive to both narrow- and broad-peak synchrony.

current model, this involved a fixed number of motor units ($n = 6$) that were selected to align discharge times, which resulted in similar values for the synchrony indexes across the pool at a given force, but differences among force levels. Because more motor units are recruited at higher forces, synchrony was imposed on a lesser fraction of the active pool. The strategy used by Taylor and Enoka (2004) was to apply a fixed proportion of common synaptic inputs. It is not known

from experimental studies whether or not the amount of motor-unit synchronization changes with force.

The current model represents only the output of each motor unit, and therefore frequency modulation is limited by the discharge rate of the pool. For this reason, it was not possible to impose high-frequency modulation to the entire motor-unit pool, especially at low forces when discharge rates were low. However, a previous model with dendritic inputs at 50 Hz,

which could be modulated at 24 Hz, demonstrated that coherence peaks were present at the frequency of modulation (Taylor and Enoka 2004). Nonetheless, cross-correlation measures of short-term synchrony did not increase with common modulation even when 90% of the dendritic inputs were modulated at 24 Hz. This result suggests that short-term synchrony, as indicated by a peak in the cross-correlation histogram, is unlikely to be caused by common modulation at 24 Hz. Taken together with the present findings, the time over which individual discharges can be advanced or delayed may be responsible for both the cross-correlation histogram peak and the 16–32 Hz coherence observed experimentally.

Implications for experimental observations

The simulations demonstrate that the location of the peaks in the coherence spectrum depend on the shape of the cross-correlation histogram, which is influenced by the intervals that the discharge times are displaced to produce synchronous discharges. Accordingly, either the absence of significant peaks or a broad range of peaks in the coherence spectrum indicate that the alignment of discharge times involves the advancing of action potential generation over a wide range of intervals. Consequently, differences in the coherence spectra between conditions, such as movements compared with postural contractions (Kakuda et al. 1999; Semmler et al. 2002) and young and old adults (Semmler et al. 2003), provide information about the timing of the synaptic events that are responsible for the synchronous discharges.

In a computational study that involved an explicit model of the motor neuron (Taylor and Enoka 2004), branched common input produced a broad range of peaks when the dendritic conductances were inactive, but distinct peaks for combinations of high levels of active dendritic conductances and 10% of background inhibitory input. Furthermore, the amplitude and location of the peaks in the spectra were influenced by the ratio of fast-to-slow inward conductances. In the current simulations, short-term synchrony produced peaks only in the 16- to 32-Hz band of the coherence spectrum (Fig. 4H), whereas the neuronal model was capable of producing multiple bands of peaks (Fig. 11 in Taylor and Enoka 2004), including the peak in the 0- to 5-Hz band that has been observed experimentally (DeLuca and Erim 2001; Farmer et al. 1993b; Kakuda et al. 1999; Mills and Schubert 1995; Semmler et al. 2002, 2003).

The bandwidth of peaks in the coherence spectrum can also vary for the conditions of motor-unit synchronization and common oscillations. The strategies used to impose motor-unit synchronization in the present study and to provide branched common input to motor neuron models (Halliday 2000; Taylor and Enoka 2004) resulted in broader peaks in the coherence spectrum compared with those due to imposed common oscillations. Results were mixed, however, on the magnitude of coherence with the two types of inputs with one study finding that the peak magnitudes in coherence were greater for the common oscillations (Halliday 2000) and another study reporting the converse result (Taylor and Enoka 2004).

Summary

The results indicate that the three indexes derived from the cross-correlation histogram and the peak in the 16- to 32-Hz

band of the coherence spectrum can be influenced by motor-unit synchronization. Moreover, the broad peak in the 16- to 32-Hz band of the coherence spectrum can be caused by the 30-ms time limit within which discharge times were adjusted to produce motor-unit synchronization. In contrast, previous studies found that imposed oscillations did not influence the peak in the cross-correlation histogram and only influenced the coherence magnitude at the frequency of the oscillation. Although the processes that lead to motor-unit synchronization are not fully understood, the current results suggest that coherence peaks may not result exclusively from oscillations in CNS drive. Therefore caution is necessary in the interpretation of the 16- to 32-Hz band in the coherence spectrum.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the insightful comments of Dr. Simon Farmer in the development of this manuscript.

GRANTS

The National Institute of Neurological Disorders and Stroke supported this work with award NS-42734 to R. M. Enoka.

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