Neuromuscular mechanisms and neural strategies in the control of time-varying muscle contractions

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Erimaki S, Agapaki OM, Christakos CN. Neuromuscular mechanisms and neural strategies in the control of time-varying muscle contractions. J Neurophysiol 110: 1404–1414, 2013.—The organization of the neural input to motoneurons that underlies time-varying muscle force is assumed to depend on muscle transfer characteristics and neural strategies or control modes utilizing sensory signals. We jointly addressed these interlinked, but previously studied individually and partially, issues for sinusoidal (range 0.5–5.0 Hz) force-tracking contractions of a human finger muscle. Using spectral and correlation analyses of target signal, force signal, and motor unit (MU) discharge, we studied 1) patterns of such discharges, allowing inferences on the motoneuronal input; 2) transformation of MU population activity (EMG) into quasi-sinusoidal force; and 3) relation of force oscillation to target, carrying information on the input’s organization. A broad view of force control mechanisms and strategies emerged. Specifically, synchronized MU and EMG modulations, reflecting a frequency-modulated motoneuronal input, accompanied the force variations. Gain and delay drops between EMG modulation and force oscillation, critical for the appropriate organization of this input, occurred with increasing target frequency. According to our analyses, gain compensation was achieved primarily through rhythmical activation/deactivation of higher-threshold MUs and secondarily through the adaptation of the input’s strength expected during tracking tasks. However, the input’s timing was not adapted to delay behaviors and seemed to depend on the control modes employed. Thus, for low-frequency targets, the force oscillation was highly coherent with, but led, a target, this timing error being compatible with predictive feedforward control partly based on the target’s derivatives. In contrast, the force oscillation was weakly coherent, but in phase, with high-frequency targets, suggesting control mainly based on a target’s rhythm.

The MU activity underlying time-varying muscle force was first systematically examined by De Luca and colleagues for muscle contractions attempting to match force output to slow ramp and triangular visual targets. The observation of essentially synchronized variations of MU firing rates that paralleled the voluntary force variations (De Luca et al. 1982; De Luca and Mambrito 1987) led to the notion of a common drive to the MN population (De Luca and Erim 1994).

Following these influential studies, various investigations examined the firing of MUs during force tracking of sinusoidal (predictable) visual targets. Linear systems analyses were used to study MU activity in relation to force output oscillation; dependencies on the target’s frequency were also considered. The reported results have provided valuable information, such as MU firing modulations exhibiting widespread synchrony and similar phase-leads over the quasi-sinusoidal force (Erimaki and Christakos 1999, 2008; Iyer et al. 1994; Knight and Kamen 2007; van Bolhuis et al. 1997). A tendency for the modulation strength to increase with increasing target frequency has also been observed (Iyer et al. 1994; Sosnoff et al. 2005). However, the current understanding of how the underlying input to the MNs is organized remains partial, in particular as regards muscle transfer characteristics, which are expected to influence this organization, and employed neural strategies as well as associated control modes.

Regarding the transformation of modulated MU population activity (EMG) into quasi-sinusoidal muscle force, a systematic investigation of the frequency dependence of amplitude and time relations is essential for exposing relevant transfer properties (linearity, gain, phase). However, there is only one related study that demonstrated a drop of modulation phases in individual MUs, relative to the force oscillation, as modulation frequency increased (van Bolhuis et al. 1997).

Regarding neural strategies, a systematic study of amplitude and time relations of force output oscillation to sinusoidal target is again crucial for assessing control mechanisms but has so far not been performed. Such amplitude relations may contribute to the understanding of how the control of force amplitude takes gain behaviors into account. Similarly, force/target time relations may do the same with respect to the way the control of force timing takes phase behaviors into account. Furthermore, the examination and assessment of timing mechanisms in this case of predictable visual targets can be properly guided by principles of predictive control (Jagacinski and Hah 1988; Ware 1972). Accordingly, prediction of a target’s future values is based on extrapolation using the target’s visually sensed trajectory and its derivatives or, equivalently, visual
predictive signals (Miall and Jackson 2006). Such feedforward control was previously assumed in studies of slow motion tracking (Jagacinski et al. 1993; Weir et al. 1989).

Finally, it is important that the interlinked questions of muscle transfer characteristics and neural control strategies, which have so far been considered individually, be examined in combination.

Therefore, to gain further insight into the neuromuscular mechanisms and neural strategies involved in muscle force control, we studied sinusoidal force-tracking contractions of the first dorsal interosseous (FDI) muscle in healthy adults. We applied spectral and correlation analyses to simultaneously recorded MU discharges, surface EMG, muscle force signal, and sinusoidal target having frequency within a broad range. Using our results, we addressed three main issues, with an emphasis on frequency dependence: 1) modulated MU firing, to assess features of the underlying neural input to the MN population that are reflected in MN activity (see Farina et al. 2013); 2) dynamic relation between EMG modulation and force output oscillation in terms of coherence, gain, and delay; and 3) dynamic relation between force oscillation and target signal, to acquire information on the organization of the motoneuronal input, including employed control modes. We thus jointly considered various aspects of force control, in an inclusive experimental paradigm that extends from the level of motoneuronal input and MU firing to that of electrical muscle activity and output force, all in relation to the target signal.

The reported results have been presented in an abstract (Christakos et al. 2011).

METHODS

Participants

A total of thirty-nine participants (23 men, 16 women, aged 21–37 yr) volunteered for the experiments. All were right-handed according to self-report and had normal or corrected to normal vision. None of them reported any neurological or neuromuscular disorder. The study conformed to the standards set by the latest revision of the Declaration of Helsinki. The protocol was approved by the Ethics Committee of the University of Helsinki. All participants reported any neurological or neuromuscular disorder. The study conformed to the standards set by the latest revision of the Declaration of Helsinki. The protocol was approved by the Ethics Committee of the University of Helsinki. None of the subjects had also participated in the trials of data set 1. The target’s mean level and amplitude on the oscilloscope were common across contractions. Across subjects, this level corresponded to a mean force of ~10% MVC (8–12%) representing a weak to moderate contraction; the target amplitude corresponded to ~28% of mean force and was thus close to the mean amplitude of the force oscillations in data set 1. Across contractions, the relative amplitude of the force oscillation was in the range of 8–54% of mean force level (mean 27%, SD 8.7%). No MU recording was attempted in these experiments. Importantly, in this experimental design using a common target amplitude, differences in contraction speed were almost exclusively due to the different target frequencies.

For both data sets, simultaneous 2-min records were obtained of the target sine wave, the muscle force signal, and the filtered (0.25 Hz to 2.5 kHz) surface EMG (using Ag/AgCl disk electrodes). For data set 1, filtered (0.25 Hz to 2.5 kHz) intramuscular EMG (using bifilar nichrome wire electrodes, 40 μm) of the FDI muscle was additionally recorded. In all cases, the data were digitized at 5 kHz and stored with the program LabVIEW.

Data Processing and Analyses

Discrimination of single-MU spike trains in the intramuscular electrical activity was performed by combining a threshold operation and manual sorting. It provided one and, in relatively few cases, two or three MUs per recording (overall, there were 13 pairs and 1 triplet of simultaneous MUs). Spike trains were represented as sequences of “zeros” and “ones.” Data set 1 comprised 154 discriminated MUs. The surface EMG signal was full-wave rectified. All recorded signals, including the sequences representing spike trains and the rectified EMG, were subsequently low-pass filtered at 250 Hz and resampled at 500 Hz for analysis. The filtering was digital and introduced no time shifts (Christakos et al. 1984). Analyses were performed in both the frequency and the time domain with MATLAB (The MathWorks, Natick, MA) as follows.

Frequency-domain analyses, performed via the fast Fourier transform on pairs of signals, included (Wang et al. 2004) 1) segmentation of the 2-min time series into sixty 2-s-long segments; 2) mean removal and windowing (Hanning) for each data segment; 3) computation of the auto-spectra and the cross-spectrum from each pair of simultaneous segments; and 4) final estimation of the auto-spectra (absolute power) and the cross-spectrum of the signal pair by averaging the estimates from the individual segments. Furthermore, for the MU spike trains and the EMGs, the relative-power spectra were calculated by dividing the absolute-power spectra by the total power.

The coherence spectrum for each signal pair was subsequently estimated as the squared modulus of the cross-spectrum divided by the product of the individual auto-spectra. This spectrum represents a measure of the degree of linear correlation between two signals as a function of frequency and is normative (values between 0 and 1.0).

For the 60 segments used in the spectral analyses of this study, and for the smooth data tapering that was employed for leakage suppression,
the threshold for a significant coherence at the 99% confidence level is ~0.08 (Rosenberg et al. 1989). It is represented by a horizontal dashed line in the coherence plots.

Importantly, the modulation component in the auto-spectrum of MU firing, expressed as relative power, represents the variations of the MU’s instantaneous firing rate, i.e., the modulation strength. The same component, expressed as absolute power, represents the frequency-modulated train of the MU action potentials. It thus additionally reflects the characteristics of the action potentials, predominantly their squared amplitude. In analogy to the above, the relative power of the EMG modulation component represents the combined rate modulations of the active MUs, with weights reflecting the differing characteristics of the action potentials among the MUs. It thus represents an “effective rate modulation” in the active MU population, which is involved in the generation of quasi-sinusoidal force. At the same time, the absolute power of the EMG modulation component represents the sum of frequency-modulated trains of action potentials from the different active MUs. It should be noted that this sum is the actual input for the EMG/force transformation studied here.

Time-domain analyses included computations of instantaneous (and mean) MU firing rates and cross-correlation functions for MU/force, EMG/force, and force/target pairs. For the last pair, histograms of the time differences between successive maxima of the force and target signals were also constructed.

Measurement of MU Synchrony

The method employed for detection and quantification of rhythmical synchrony within a neural population (population synchrony) has been presented in Christakos (1994, 1997) and applied to detailed analyses of MU synchrony in Christakos et al. (2006, 2009) and Erimaki and Christakos (1999, 2008). In brief, coherence and cross-correlation computations performed on a sample of pairs of simultaneously recorded MU and force signals were used for 1) detection of MU modulation synchrony, through the observation of at least one significant MU/force coherence in the sample; 2) estimation of the extent of the synchrony within the active MU population as the proportion of significant such coherences in the sample; and 3) estimation of MU phases in terms of time advances over the force oscillation (common reference signal).

It should be stressed that when the MU synchrony is widespread and the MU time advances show a narrow distribution (within 25% of the period of the synchrony), the MU/MU coherence value approaches the squared value of the MU/force coherence (Christakos 1997). Thus the squared MU/force coherences in a sample yield an approximate measure of the strength of the synchrony in terms of MU/MU coherences.

Frequency Response for EMG/Force Transformation

Frequency responses were computed for the recorded EMGs/MUs pairs, i.e., the input/output pairs for the transformation of modulated electrical muscle activity into a force oscillation. The EMG/force coherence was first used to verify the linearity of this transformation at the modulation frequency (f_m). Then the frequency response at f_m was estimated as the ratio of the cross-spectrum of the pair and the auto-spectrum of the input (Christakos et al. 1987):

\[ G_{xy}(f) = \frac{S_{xy}(f)}{S_{xx}(f)}; \quad f = f_m \]

where x(t) and y(t) are the EMG and the force signal, respectively.

The frequency response of a linear system is a complex function of frequency. Its magnitude is the gain of the transformation, representing the amplitude relation between input and output. Its angle is the phase of the transformation, representing the time relation between input and output. This time relation may, however, also be measured using cross-correlation computations between input and output.

Cross-correlation functions were computed between EMGs, or MU spike trains, and force signals, as they provide straightforward information on the respective time relations. Even when the coherence between such signals is too low to permit reliable phase estimation from the “noisy” cross-spectrum, the general form of the cross-correlogram can at least provide a rough estimate of the time relation between the signals.

Statistical Analyses

All data were analyzed with the SPSS v13.0 statistical package. Estimates of the Spearman rank-order correlation coefficient were used to examine possible relationships between such variables as MU firing rate, mean level of contraction, and MU/force coherence. Linear regression analysis was used to assess the effect of the MU modulation frequency on the r.m.s. variation of instantaneous firing rate. In data set 2, the paired-samples t-test was used to compare the size of the force auto-spectral component to that of the common target. All tests were considered significant at the \( P < 0.05 \) level.

RESULTS

Motor Unit Firing Modulations and Associated Synchrony

Each of the 139 muscle force records in data set 1 (METHODS) exhibited a quasi-sinusoidal oscillation at the tracking frequency. In all cases, frequency-modulated discharges were evident in the 2-min MU record(s) and surface EMG, in the form of rhythmically varying spike density, or rhythmical bursts, at the frequency of the force oscillation. For every one of the 154 discriminated MUs, this firing modulation was manifested as a distinct auto-spectral component exhibiting coherence to the voluntary component of the force and a time advance over it. The same applied to the modulation of the surface EMG.

Figure 1 shows an example of analyses of recorded signals during a 3.0-Hz muscle contraction. A dominant component is seen in the force auto-spectrum (Fig. 1, left, vertical dashed line), at the frequency of the voluntary force oscillation (see 2-s segment, Fig. 1, center). The corresponding large and sharp peak in the MU auto-spectrum (relative power) is the modulation component of the MU’s discharge. This component represents variations of instantaneous firing rate (METHODS), where the variations corresponding to the 2-s segment of this example are also depicted in Fig. 1, center. The particular component is highly coherent with the principal component of the force, and judging from the location of the central peak in the oscillatory MU/force cross-correlogram (Fig. 1, center), it exhibits a considerable time advance (120 ms) over the same.

Notably, the MU auto-spectral deflection near 20.0 Hz (Fig. 1, left, arrow) represents the carrier signal of the MU’s modulated discharge; the carrier rate equals the mean firing rate of an MU for a steady contraction at the same force level (Iyer et al. 1994), as was also confirmed in this particular example. The 20-Hz carrier component exhibits no coherence to the force signal.

In Fig. 1, right, the auto-spectrum (relative and absolute power) of the recorded surface EMG during the particular contraction also exhibits a clear modulation component. This component is again highly coherent with the MU modulation component.

These features were typical of the sample of the various signals in data set 1, as described below.
Auto-spectral analyses. The component representing the voluntary force oscillation dominated the force auto-spectrum in all cases, and distinct MU and EMG modulation components were also present in the respective auto-spectra. For all studied contractions, the frequency of the voluntary component of the force was the same as that of the modulation components of the recorded MU(s) and the surface EMG.

The size (relative spectral power) of the modulation component varied widely (range 0.0004–0.014; mean 0.0036, SD 0.0034) among the 154 MUs, reflecting a broad range of r.m.s. variation of instantaneous firing rate in the time records: 2.65–13.62 pulses per second (pps) (mean 6.4, SD 2.1). However, linear regression analysis on the sample of r.m.s. values for the 154 MUs revealed a statistically significant, general tendency for the r.m.s. modulation to increase as the modulation frequency, $F_m$, increased: r.m.s. = 5.55 + 0.5 $F_m$; $P = 0.003$. Accordingly, the average rise of the r.m.s. value between modulations up to 1.0 Hz and modulations above 4.0 Hz was of the order of 30%.

It should be noted that the study of the frequency dependence of the overall strength of MU rate modulations, in response to the motoneuronal input, in data set 1 is complicated by a number of factors. These are the differing 1) sizes of randomly selected MUs, 2) mean force levels in the different contractions and associated MU mean firing rates (mean 12.6 pps, SD 2.8), and 3) amplitudes of sinusoidal targets. On the other hand, the EMG modulation component (relative power) provides a representative view of combined rate modulations in the population of active MUs, including their individual degrees of participation in the generation of the force oscillation (METHODS). It thus allows direct comparisons over the modulation frequency, as long as the force level and the target amplitude are common in the different contractions. This is roughly the case in data set 2, which was created and used as a second step in the study of the frequency dependence of the modulation strength. At the same time, the absolute power of the modulation component allows direct comparisons over $F_m$ regarding the input for the EMG/force transformation (METHODS).

Coherence analyses. In agreement with our previous report using a portion of data set 1 (Erimaki and Christakos 2008), the estimated MU/force coherence at $F_m$ varied widely among the 139 contractions and the 154 MUs of the present study (observed range 0.13–0.97), although for each of 13 pairs and
1 triplet of simultaneous MUs it was within 10% of the average value. This coherence was generally high (mean 0.71, SD 0.18), as also seen in Fig. 2A, which depicts the coherence data from the sample of 154 MUs, grouped according to the modulation frequency.

Statistical analyses indicated no significant relationship of the MU/force coherence to 1) the modulation frequency (Spearman rank correlation coefficient 0.112, \( P = 0.163 \)) and 2) the mean force level (Spearman \(-0.136, P = 0.10\)) or the MU carrier rate (Spearman 0.114, \( P = 0.171 \)). However, there was a positive relationship to the r.m.s. amplitude (\%VC) of the quasi-sinusoidal force (Spearman 0.353, \( P < 0.001 \)).

It should be noted that for all 154 MUs the MU/force coherence at \( F_m \) was statistically significant (\( >0.08 \)), i.e., every MU was coherent with other MUs in the active population. Accordingly, a widespread synchrony of MU firing modulations was present in the studied contractions, and judging from the observed mostly high MU/force coherences, this synchrony was moderate to strong (METHODS).

\**Phase analyses.** The statistically significant MU/force coherences in the sample enabled the reliable estimation of the phases of the MU modulations relative to the force oscillation via MU/force cross-correlation analysis. For every MU, the cross-correlogram to the force (e.g., Fig. 1) exhibited a large oscillation at the modulation frequency, again reflecting the correlation of the MU’s modulation to the quasi-sinusoidal force and, hence, to the modulations of other active MUs (METHODS). The location of the central peak in the cross-correlogram indicated a phase lead of the MU modulation over the quasi-sinusoidal force. This time advance varied widely among contractions and MUs and covered the range 72.0–342.0 ms (mean 140.0, SD 42.0) over the entire sample of 154 MUs. However, its values were comparable for each modulation frequency, as seen in Fig. 2B, which depicts data of the MU advances, grouped according to the modulation frequency.

Simultaneously recorded MUs showed similar, but not identical, time advances in all cases. As observed in the 13 pairs and 1 triplet of concurrently active MUs, there was a tendency for MUs firing at higher rates to exhibit longer modulation advances over the force variations (Spearman 0.67, \( P = 0.005 \)). However, such differences among MU advances were very small compared with the average advance for each pair (mean 8%, SD 8%). More generally, over the entire sample of 154 MUs the range of advances per target frequency represented a small fraction (up to 15%) of the modulation period (\( T_m \)), i.e., the MU modulations were essentially in phase.

This phase similarity enabled the estimation of MU/MU coherences by squaring the observed MU/force coherences (METHODS). The range of the MU/MU coherences was found to be 0.017–0.95 (mean 0.50, SD 0.22), representing moderate to strong modulation synchrony among active MUs.

Interestingly (Fig. 2B), the MU-force time advance generally decreased as the modulation frequency, \( F_m \), increased. However, when expressed as a fraction of \( T_m \) (relative advance), it exhibited a systematic rise with increasing \( F_m \). As seen in Fig. 2C, the relative advance increased in a fairly linear fashion from \(-0.10\) to 0.45 as \( F_m \) increased from 0.5 Hz to 5.0 Hz.

Overall, the MU behaviors described in this section reflect features of the neural input to the MNs and thus allow inferences on this input.

\**Relationship Between EMG Modulation and Force Output Oscillation**

To obtain a more global view of how the modulated activity of the ensemble of active MUs is transformed into a muscle force oscillation, we performed the same analyses as above on the EMGs and force signals of the 136 contractions of data set 2. These activities were obtained under the condition of common level and common amplitude for the sinusoidal targets.

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**Fig. 2.** Dependencies of MU/force coherence and time advance on the modulation frequency \( F_m \) (data set 1, 154 MUs). Bars represent means ± SE. The relative MU/force time advance in C is expressed as a fraction of the modulation period \( T_m = 1/F_m \). Note in A the high MU/force coherences for all modulation frequencies; in B the decline of MU time advances over the force with increasing \( F_m \); and in C the fairly linear relationship between relative MU advances and \( F_m \).
Increasing Fm, being frequencies up to 1.0 Hz. However, it progressively rose with 0.0005 of the total EMG power (relative power) for modulation contractions of power to increase with Fm: absolute power for the 136 contractions confirmed the clear tendency for this regression analysis on the sample of values of absolute power Fm)\times10^{-2}, P < 0.0005. Accordingly, the average rise of the power between modulations up to 1.0 Hz and modulations above 4.0 Hz was by a factor of \sim 6.0. Equivalently, the input for the EMG/force transformation was \sim \sqrt{6.0}, i.e., \sim 2.5 times larger (150% increase).

Auto-spectral analyses. The size of the force component across contractions showed no difference from the common targets’ size (paired-samples t-test: \( t = -0.511, \text{df} = 135, P = 0.610 \)).

As shown in Fig. 3A, the EMG modulation component in the contractions of data set 2 represented a fraction of the order of 0.0005 of the total EMG power (relative power) for modulation frequencies up to 1.0 Hz. However, it progressively rose with increasing Fm, being \sim 2.5 times larger (0.0013) for modulations above 4.0 Hz. According to Fig. 3B, a rise with Fm was also exhibited by the absolute power of the EMG modulation component, which represents the superimposed trains of MU action potentials that act as the input for the EMG/force transformation (METHODS). The slope of this rise is much steeper than that of the relative power in Fig. 3A. Linear regression analysis on the sample of values of absolute power for the 136 contractions confirmed the clear tendency for this power to increase with Fm: absolute power = (2.0 + 26.1 Fm)\times10^{-4}, P < 0.0005. Accordingly, the average rise of the power between modulations up to 1.0 Hz and modulations above 4.0 Hz was by a factor of \sim 6.0. Equivalently, the input for the EMG/force transformation was \sim \sqrt{6.0}, i.e., \sim 2.5 times larger (150% increase).

These findings demonstrate how the modulation strength in the MU population (relative EMG power) and the amplitude of the EMG modulation component (absolute power) vary with Fm. They too have implications for the underlying motoneuronal input.

Coherence and gain analyses. The EMG/force coherence at Fm was very high for all target frequencies (Fig. 4A), indicating that the EMG modulation component and the quasi-sinusoidal force were linearly related. This observation allows the estimation of linear system parameters (gain, phase) characterizing the transformation of modulated electrical muscle activity into quasi-sinusoidal force.

In Fig. 4B, the gain of the EMG-force transformation exhibits a clear decline with increasing Fm, its value at 5.0 Hz being \sim 3 times smaller than that at 0.5 Hz. Thus the efficiency of the synchronous MU modulations in causing muscle force variations progressively decreased as Fm increased. The above-described rise of the EMG component to meet force amplitude requirements describes the way in which the gain drop influences the organization of the motoneuronal input.

Phase analyses. In analogy to the MU behaviors (Fig. 2, B and C), the EMG modulation component led the voluntary force oscillation in all cases, the range of the EMG time advances being similar to that of the MU time advances. The absolute EMG advances (mean, SE) in Fig. 4C decrease with increasing Fm. At the same time, in Fig. 4D, the relative EMG advances (fractions of Tm) increase almost linearly with Fm. Using the best-fit straight line, this relationship can be described as relative advance = 0.10 + 0.07 Fm. Equivalently, the absolute advance (ms) is given as absolute advance = 70 + Tm\times10.

This observation highlights dependencies of the time relation between modulated electrical muscle activity and force output oscillation, which are crucial for the correct timing of the motoneuronal input.

Force and EMG Variations in Relation to Sinusoidal Targets

As a final step, we considered the time relation of the subjects’ force oscillations to the common-amplitude sinusoidal targets in the 136 contractions of data set 2, to gain insight into the timing mechanisms of the control of force-tracking contractions. Specifically, we performed force/target coherence and cross-correlation analyses to assess the degree and frequency dependence of the subjects’ “success” in following a target. In particular, the jitter in the subjects’ force rhythm and the overall time relation of this rhythm to the target signal were examined.

Regarding time jitters, the coherence of the force oscillation to the sinusoidal target was very high (>0.80) for low-frequency targets. However, it progressively declined for targets above \sim 1.5 Hz, being <0.50 for targets above 2.5 Hz and as low as 0.20 above 4.0 Hz (Fig. 5A). This dependence indicates an increase in time jitter with increasing target frequency. Owing to the very high EMG/force coherence (Fig. 4A), the EMG coherence to the target (not shown here) exhibited a similar behavior.

Regarding overall time relations, the situation was complicated in that the force oscillation in every contraction exhibited, for variable numbers of cycles, time delays interchanged with advances over the target sine wave. However, force/target correlation analyses revealed that, overall, the force oscilla-
Relative to the peak of the target's trajectory as well as the create a view of the timing of the EMG modulation peak mode. Therefore, estimated EMG/target advances were used to the time points for which the force and target peaks would occur, indicating that the EMG-target advances tended to be near 0 above 2.5 Hz. With increasing target frequency, from over 100 ms at 0.5 Hz to 0.90, indicating a linear relationship between EMG and force over the 5-Hz band of modulation frequencies; in B the decline of the gain with increasing F_m; in C the decline of the absolute time advance with increasing F_m; and in D the fairly linear relationship between the relative time advance and F_m.

Representative examples of histograms are depicted in Fig. 5, C and D. In Fig. 5C, the force advances (positive time axis right to vertical dashed line) over the 1.0-Hz target are overall much more frequent than the delays (negative time axis). In fact, the ratio of the number of advances in the histogram’s right half to the total number of intervals is >0.90, indicating that the advances were more than nine times as frequent as the delays. In contrast, advances and delays relative to the 3.0-Hz target had similar incidences (Fig. 5D), the same ratio now being ~0.50.

Over the entire sample of contractions, the particular ratio gradually decreased with increasing target frequency, from values near 1.0 at 0.5 Hz to values near 0.50 at frequencies above 2.5 Hz. Equivalently, the average time advance of the force oscillation per contraction in Fig. 5B gradually decreased with increasing target frequency, from over 100 ms at 0.5 Hz to near 0 above 2.5 Hz.

The observed timing error (force advance) for low-frequency targets, up to 2.5 Hz, and to be in phase with 3.0- to 5.0-Hz targets (Fig. 5B). This tendency, already evident in the records, was also clarified and explained by histogram analyses of such time advances and delays.

There are significant differences in the absolute and relative time advances between the 1.0- and 3.0-Hz targets, with the former having a greater absolute time advance and the latter having a greater relative time advance. These behaviors cast a light on control modes employed during force-tracking contractions.

**DISCUSSION**

Our results provide a broad view of features and interrelations of MU firing, muscle activities, and sinusoidal visual targets during force-tracking tasks performed over a wide frequency range. They thus form a basis for considering the issues of neuromuscular mechanisms and neural strategies involved in force control. Certain of these results (MU firing modulation, EMG/force transformation, and gain behavior and compensatory mechanisms), as summarized and commented on below, extend previous observations and provide new information on the participation and impact of parallel mechanisms. Other results (force/target relation, timing mechanisms, control modes) represent innovative findings. More generally, the unified examination of the above two interlinked issues in the same experimental paradigm represents an approach not previously used in the study of force control. The same applies to the force/target analyses performed.
Our main observations show 1) widespread, in-phase, and moderate-to-strong synchrony of MU modulations, irrespective of force level and modulation frequency, reflecting a frequency-modulated common input to the MNs; 2) linear relationship between EMG modulation and force output oscillation, allowing the demonstration of gain and delay drops for the EMG/force transformation as the modulation frequency increases; 3) enhanced strength of the EMG component at high modulation frequencies, indicating compensatory modifications of the common input, combined with other compensatory effects one of which is very strong; 4) strong time bonds (coherence) between force oscillations and low-frequency targets, and loose relations for high-frequency targets, suggesting differences in control between the two conditions; and 5) lead-lag interchanges between force oscillations and targets, with an overall tendency for such oscillations to lead slow targets and to be in phase with fast targets, the latter behaviors being compatible with distinct control modes.

MU Firing Modulations and Underlying Neural Input

The observed spectral composition of MU spike activities, exhibiting modulation and carrier components, is consistent

Table 1.  Frequency dependence of EMG/target time advances

<table>
<thead>
<tr>
<th>Target Frequency</th>
<th>0.5 Hz</th>
<th>1.0 Hz</th>
<th>1.5 Hz</th>
<th>2.0 Hz</th>
<th>2.5 Hz</th>
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<tbody>
<tr>
<td>TA/Tm</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Range</td>
<td>0.09–0.24</td>
<td>0.18–0.38</td>
<td>0.23–0.41</td>
<td>0.16–0.47</td>
<td>0.21–0.48</td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>0.17 (0.05)</td>
<td>0.29 (0.13)</td>
<td>0.32 (0.07)</td>
<td>0.32 (0.08)</td>
<td>0.33 (0.09)</td>
</tr>
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Data set 2, 98 contractions. Time advances (TA) are represented as fractions of the target’s period ($T_m$).

with mathematical models of pulse-frequency modulated signals (Sanderson 1980). Notably, contrary to the Sosnoff et al. (2005) results, a distinct MU modulation component was present even for modulation frequencies below 1.0 Hz.

The significant and mostly high MU/force coherences in our sample, apart from disclosing widespread MU modulation synchrony, also enabled the reliable estimation of modulation time advances over the force oscillations. Across subjects, these MU advances were comparable per modulation frequency and very similar per contraction (in-phase synchrony).

These features are in accord with the concept of a common, frequency-modulated neural input to the MN population (De Luca and Erim 1994; see also DeLuca and Contessa 2012; De Luca and Ermini 2002; Farina et al. 2013; Farmer et al. 1993; Johnston et al. 2005, 2009; Laine and Bailey 2011; Marsden et al. 1999; Rose and Knight 2011; Semmler et al. 1997; Winges et al. 2008). As indicated by our analyses, the strength of the modulation synchrony is not related to the force level and the frequency of the force variations or, equivalently, to the level and frequency of the oscillatory common input. These new observations reveal a robust mechanism underlying MU cooperation.

The determination of the frequency and amplitude of force oscillations by volition argues for a supraspinal origin of the frequency-modulated input, a possibility also supported by reported cortical influences on MNs of various muscles (Gibbs et al. 1999; Lang and Schieber 2004; McKiernan et al. 2000; Palmer and Ashby 1992).

Two other sources possibly mediating, or influencing, the common input have been considered. Of these, the Renshaw cell system does have appropriate transfer characteristics.
(Christakos et al. 1987), yet, as shown by De Luca et al. (1982) and Erim et al. (1999), this input is observed in muscles lacking recurrent inhibition, like the FDI studied here (Katz and Pierrot-Deseilligny 1999). Similarly, the common input exists in muscles lacking spindle (Kamen and De Luca 1992). More generally, the ischemic block of spindle action does not significantly affect the MU modulations and synchrony (Erimaki and Christakos 2008). However, according to the De Luca et al. (2009) study, spindle feedback in various muscles reduces the common input. Thus spindle action may have some modulatory effect on the spinally descending signals, and the same could also hold for recurrent inhibition if present.

**Frequency Dependence of EMG/Force Transformation: Adaptation of Common Input**

The observed very high EMG/force coherence for all modulation frequencies allowed the computation of reliable gain and phase estimates characterizing the (linear) transformation of the modulated MU population activity into quasi-sinusoidal force.

Regarding the gain of the EMG/force transformation, its decline with increasing modulation frequency is a manifestation of the low-pass filtering property of muscle (Mannard and Stein 1973; Milner-Brown et al. 1973). In a related study in which the visual target consisted of two superimposed sine waves at 0.15 Hz and 0.45 Hz, Knight and Kamen (2007) also observed “less change in force per change in MU rate” at the second harmonic frequency.

As follows from our results, the organization of the common input takes into account the gain drop through adaptation of the input’s modulation strength. Such an adaptation is expected, since for any given tracking frequency the amplitude of the force oscillation can be voluntarily determined and have any desired value. This adaptation takes place in the presence of two other actions that are described below.

First, increased MN firing sensitivity to higher-frequency oscillatory inputs (injected currents) has been demonstrated in the intracellular study by Baldiressa et al. (1984), this increase between frequencies up to 1.0 Hz and frequencies above 4.0 Hz being of the order of 15–20% (their Fig. 5). At the same time, a corresponding increase of r.m.s. rate modulation by ~30% was observed in our sample of 154 MUs. Clearly, the rise above that expected from enhanced MN sensitivity is due to a stronger motoneuronal input.

Second, the higher contraction speeds required at higher target frequencies are achieved through the rhythmic activation/deactivation of higher-threshold MUs (Budingen and Freund 1976) exhibiting larger and faster action potentials and twitches (Freund 1983). The cyclical recruitment and derecruitment of progressively larger MUs as the target frequency increases contributes toward a sharp augmentation of the relative EMG modulation power (RESULTS) or, equivalently, an enhancement of the “effective rate modulation” for the active MUs (METHODS). More importantly, it causes an even sharper augmentation of the absolute such power or, equivalently, a large enhancement of the input for the EMG/force transformation. As described in RESULTS, this enhancement between frequencies up to 1.0 Hz and frequencies above 4.0 Hz was by a factor of 150% and led to complete gain compensation.

According to our consideration and analyses of these new findings, the cyclical activation/deactivation of higher-threshold MUs provides most of the overall gain compensation. The particular MU behavior is clearly influenced by the increased MN sensitivity and the modified motoneuronal input as frequency increases, but it acts far beyond their 30% effect in regard to gain compensation. Therefore, on the basis of all the above effects compensating for the gain drop, the modulated motoneuronal input is ultimately adapted to the target’s amplitude requirements.

Finally, the accompanying linear rise of the relative EMG/force time advance (see also Van Bolhuis et al. 1997), and the corresponding changes of the absolute such advance, describe phase behaviors that are critical for the correct timing of the common input. It is worth noting that the 70-ms constant part in the expression describing the relation between absolute time advance and modulation period (RESULTS) is of the order of the MU contraction times in the FDI muscle (Milner-Brown et al. 1973).

**Control Modes**

Sosnoff et al. (2005) interpreted the increase in relative EMG power at higher frequencies as reflecting increased contribution from feedforward control processes compared with feedback processes (see also Sosnoff and Newell 2005). Indeed, feedback corrections become effective in the future, since a considerable delay (~400 ms) is inevitable because of the sensorimotor transformations (Miall 1996). Thus visual feedforward (predictive) signals can reasonably be assumed to underlie the tracking of predictable targets (see Miall and Jackson 2006). As already noted in the introduction, a feedforward mode was assumed in previous studies of motion tracking of very slow (<0.5 Hz), predictable targets (Jagacinski et al. 1993; Weir et al. 1989) for which intermittent feedback corrections are rare (Pew et al. 1967).

The features disclosed by our coherence and phase analyses for the force/target and EMG/target pairs provide new insights into such mechanisms in the case of force control. Two of the observations refer to low-frequency tracking: 1) the strong time relations between force oscillations and slow targets, manifested as high coherences (small jitter), and 2) the tendency for force oscillations to lead such targets, the timing of common input and EMG modulations being influenced by the target’s derivatives. Both of these observations are compatible with the involvement of predictive feedforward control during force-tracking contractions, based in part on visual inputs regarding a target’s velocity and acceleration profiles. In this model, the control mode seems therefore the main determinant of the common input’s, fairly erroneous, timing. The particular mode is analogous to the one assumed in studies of manual interception of moving targets (Port et al. 1997; Soechting and Flanders 2008; Soechting et al. 2009). Importantly, this control mode could be related to the image velocity/acceleration signals that are known to drive smooth pursuit eye movements (Krauzlis and Lisberger 1991).

Two other observations refer to higher-frequency tracking: 3) the weak (low coherence, large jitter) but 4) in-phase time relations of force oscillations to targets above ~2.5 Hz. Taken together, these two observations suggest that, as the target’s frequency increases, progressively less attention is paid to the target’s profile and more to the target’s rhythm. Indeed, sub-
jects, according to self-report, did not try to mimic the trajectory of fast targets; they instead followed a target’s basic rhythm as manifested in the successive peaks of the sine wave.

This transition toward rhythm-related control for fast targets might be due to the sensorimotor delay imposing a limit to the low-frequency mode, namely, target periods > 400 ms (sensorimotor delay). This possibility is in agreement with the observed coherence and phase behaviors for target frequencies > 2.5 Hz (Fig. 5, A and B). Another limiting factor could reflect constraints regarding the above-mentioned image velocity/acceleration signals. In a study of motion tracking of oscillatory visual targets (Roerdink et al. 2005), smooth pursuit eye movements were essentially absent for target frequencies above 1.5 Hz. This behavior is consonant with our observation of sharply declining force/target coherence and time advance for targets above 1.5 Hz (Fig. 5, A and B).

Conclusions

Based on analyses of MU and muscle activities during force tracking of sinusoidal visual targets, certain of the present findings substantially extend the current understanding of underlying neuromuscular mechanisms while other findings do the same regarding neural strategies. The former findings may have relevance for the more general case of complex force variations, or variations that do not involve visual tracking. These include the gain drop between EMG and force for fast variations, the accompanying strengthening of common input and EMG modulation for compensation, and the decline of the EMG(force) time advance. The latter findings may pertain to situations in which the motor output provides continuous matching to external visual inputs representing desired force trajectories. These include the ability of continuous tracking of slow trajectories through predictive control, albeit with systematic timing errors, and the more free control for fast trajectories.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: S.E. and C.N.C. conception and design of research; S.E. and O.M.A. performed experiments; S.E., O.M.A., and C.N.C. analyzed data; S.E., O.M.A., and C.N.C. interpreted results of experiments; S.E. and O.M.A. prepared figures; S.E., O.M.A., and C.N.C. edited and revised manuscript; S.E., O.M.A., and C.N.C. approved final version of manuscript; C.N.C. drafted manuscript.

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