Effect of contraction level and magnitude of stretch on tonic stretch reflex transmission characteristics

PETER D NEILSON, JANET McCAUGHEY

From The Spastic Centre Research Unit, Department of Neurology, The Prince Henry Hospital and School of Medicine, University of New South Wales

SUMMARY Electromyogram tonic stretch reflex responses were recorded from biceps brachii muscles in normal and cerebral palsied subjects sustaining either 10% or 20% of maximum voluntary contraction and attempting to keep the elbow stiff in a fixed position. The muscle was stretched by a sinusoidal perturbation applied by the experimenter to the elbow angle. Five different amplitudes of stretch were employed ranging from 1.67 to 10.0 degrees peak to peak variation of elbow angle. Spectral analysis of the rectified and filtered electromyogram revealed "noisy" sinusoidal reflex responses with negligible harmonic distortion but the amplitude of the reflex responses did not increase linearly with the amplitude of stretch. An analysis of variance showed that for both groups of subjects the gain of the tonic stretch reflex increased significantly (p < 0.001) with contraction level and decreased significantly (p < 0.001) with magnitude of stretch. This finding illustrates that both magnitude of stretch and level of contraction need to be carefully controlled when measures of tonic stretch reflex responses are used to assess changes of muscle tone.

Muscle tone is assessed clinically by experiencing the resistance to passive movement of a limb. This is a subjective assessment and clearly an objective measure is required. Measurement of the force-displacement characteristics of a joint is complicated by the fact that more than one muscle usually operates across each degree of freedom of movement and each muscle usually operates across more than one joint. The task can be simplified by measuring the contribution of a single muscle for a small range movement. The tonic stretch reflex (TSR) provides a mechanism by which muscles actively resist passive stretching and a quantitative measure of TSR transmission characteristics can provide an objective assessment of muscle tone. Such a measure is useful, for example, in assessing the efficacy of treatment procedures aimed at reduction of rigido-spasticity in cerebral palsied patients. Measurement of the mathematical relationship between applied stretch of a muscle and the resulting electromyogram (EMG) reflex response is, however, by no means simple. Even a full-wave rectified and low-pass filtered EMG (IEMG) provides a "noisy" measure of reflex responses and consequently a statistical analysis is required.

In this regard the techniques of cross correlation and spectral analysis have proved useful and have been employed at this laboratory to compute the "best-fit" linear relationship between elbow angle perturbations and IEMG responses in biceps brachii muscle during sustained voluntary contraction. The best fit linear relationship is described graphically by gain and phase frequency response curves. Gain is the ratio of the amplitude of the IEMG reflex response to the amplitude of muscle stretch, while phase provides a measure of the timing of the IEMG reflex response relative to the applied stretch.

Two phenomena have been reported in the literature which could complicate the measurement of TSR transmission characteristics during voluntary activity. The magnitude of long-loop reflex responses increases with average contraction level and reflex stiffness of the jaw decreases as the magnitude of the stretch perturbation is increased. If TSR transmission characteristics are sensitive to either contraction level or magnitude of stretch then variations of these parameters during a test could cause measures of gain and phase to be "smeared" by statistical analysis into complex characteristics. The aim of the present study is to assess the sensitivity of TSR transmission characteristics to variations of contraction level and magnitude of stretch in both normal and cerebral palsied subjects.
Method

Five normal subjects aged 22-36 years and five cerebral palsied subjects aged 24-37 years were tested. The cerebral palsied subjects displayed a mixture of rigidospasticity and athetosis and had received some biofeedback training to teach them to sustain a steady contraction in the biceps brachii muscle. Subjects lay supine on a couch with the right arm strapped into an arm frame which restrained movement to flexion-extension about the elbow. The upper arm lay horizontally on the couch, while the forearm was vertical and supinated so that flexion movements about the 90° elbow angle involved the biceps brachii muscle. A goniometer attached to the arm frame measured elbow angle which was displayed as a deflection on an oscilloscope. A Devices 3160 amplifier was employed to record a surface electrode EMG from biceps brachii muscle and this signal was displayed on an oscilloscope so that noise and movement artefact could be detected. Good quality EMG signals were obtained and no recordings contaminated by noise or movement artefact were included in the results. The EMG was full-wave rectified and low-pass filtered in an EAI-185 analog computer to obtain IEMG signals. Two low-pass filters were employed. The first consisted of two single pole filters connected in cascade (time constant \( t_1 = t_2 = 0.03 \) s). The output from this filter was sufficiently large to follow rapid fluctuations in EMG activity and was used to detect TSR responses. The second consisted of one single pole filter with a long time constant \( t = 1.0 \) s which provided a smooth measure of the average contraction level. The average contraction level was displayed to the subject as the deflection of a pointer on a large meter. IEMG signals were calibrated by adjusting the EMG amplifier gain to produce full scale deflection on the average contraction level meter while the subject sustained a maximum contraction of the biceps brachii muscle by pulling against the experimenter. Subsequent IEMG measures were expressed as a percentage of maximum contraction.

Each subject was instructed to maintain a constant average contraction of the biceps brachii muscle at either 10% or 20% of maximum by maintaining a constant deflection of the pointer on the average contraction level meter. They were also instructed to make the elbow stiff and to keep the arm as still as possible in the ninety degree position despite disturbance forces applied to the arm by the experimenter. This required cocontraction of elbow flexor and extensor muscles. The experimenter applied a constant amplitude and constant frequency sinusoidal perturbation to the forearm by moving the elbow angle about the ninety degree position. The displacement perturbation was applied directly to the arm frame while changes in either angular displacement or frequency were monitored on an oscilloscope. There was no difficulty in overcoming the resistance of the subject’s arm and maintaining a constant sinusoidal perturbation because of the mechanical advantage provided by the arm frame. Each test lasted for one minute and although the frequency of the elbow angle perturbation was held constant at about 4-0 Hz, the amplitude of the perturbation was maintained at a different value for each test. A total of ten one minute tests corresponding to five different amplitudes of stretch (elbow angle perturbation = 1-67, 2-50, 5-00, 7-50 and 10-00 degrees peak to peak) with the subject sustaining 10% and 20% average contraction levels were given to each subject. The elbow angle and IEMG signals were recorded on an Electrodata FM tape recorder (Bandwidth 0-5-0 KHz) for subsequent analysis.

Elbow angle and IEMG \( (t_1 = t_2 = 0.03 \) s) signals were sampled synchronously at 20 samples/s and stored in computer files for subsequent cross correlation and spectral analysis described in detail elsewhere. The mean value, variance and power spectral estimate were computed for each elbow angle and each IEMG signal. The cross correlation function between elbow angle and IEMG was computed for each one minute test, together with the associated coherence, gain and phase describing the best fit linear relationship between elbow angle perturbations and IEMG responses. Coherence provides a measure of the proportion of IEMG variance at each frequency which is linearly related to elbow angle perturbations. Gain provides a measure of the average amplitude of the IEMG responses relative to the average amplitude of elbow angle perturbations and phase provides a measure of the timing of IEMG responses relative to elbow angle perturbations. The remnant IEMG power spectrum was also computed for each one minute test. The remnant IEMG power spectrum describes variations in the IEMG signal not correlated with elbow angle changes and is computed by subtracting the power spectrum of IEMG fluctuations which are correlated with elbow angle changes from the power spectrum of the total IEMG signal. A frequency resolution of 0-1 Hz for frequencies between 0-0 and 10-0 Hz was employed for the power spectral and frequency response estimates and consequently, precise measures of the frequency of both elbow angle perturbations and IEMG responses were obtained.

The remnant IEMG power spectrum provides a statistical description of IEMG fluctuations not linearly related to elbow angle perturbations. These include fluctuations due to background activity, variations of TSR transmission characteristics and nonlinear distortions of TSR responses. If a sinusoidal stimulus is applied to a linear system the response is sinusoidal with amplitude and timing determined by the gain and phase of the system. On the other hand, if the input-output relationship of the system is nonlinear then the output sinusoid will be distorted and such distortion is revealed in the power spectrum as a series of peaks at harmonics or multiples of the input frequency; the larger the amount of distortion the larger the magnitude of the harmonic peaks. The amount of harmonic distortion in IEMG stretch reflex responses can be expected to decrease as the magnitude of stretch is reduced because a nonlinear curve can be better approximated by a straight line for small variations than for large variations. IEMG and remnant IEMG power spectra from each test were examined to assess the amount of harmonic distortion in the IEMG reflex response and to determine whether or not the amount of distortion decreased as the magnitude of stretch was reduced.

A three factor analysis of variance with repeated
measures was used to test the null hypothesis that measures of gain and phase are independent of contraction level and magnitude of stretch. In each analysis factor A had two levels representing normal and cerebral palsied subject groups, factor B had two levels representing 10% and 20% contraction levels and factor C had five levels representing the five amplitudes of sinusoidal elbow angle perturbation (that is 1-67, 2-5, 5-0, 7-5 and 10-0 degrees peak to peak).

One cerebral palsied subject was completely retested using a different two pole IEMG filter with very short time constants (t1 = t2 = 0-008 s). This data was sampled at 100 samples/s and spectral analysis was performed using a frequency resolution of 0·5 Hz for frequencies between 0·0 and 50·0 Hz. By using these short time constants and broad band spectral analysis the possibility of detecting harmonic distortion in the IEMG responses was greatly increased since harmonic distortion was unlikely to have been removed by the filter and the broad band spectral analysis enabled higher harmonics to be detected if they were present in the IEMG signal. Indeed, an absence of harmonic distortion in this analysis would provide strong evidence that TSR reflex responses are not distorted by nonlinearities in TSR transmission.

Results

A typical set of elbow angle and IEMG (t1 = t2 = 0·03 s) signals from one of the cerebral palsied subjects at the five different amplitudes of stretch and at the 10% and 20% maximum contraction levels are presented in fig 1. The main results of the study can be seen in this figure. The gain of the TSR was greater at the 20% average contraction level than at the 10% average contraction level. At any one contraction level the magnitude of the steady state TSR response increased with the amplitude of the steady state sinusoidal elbow angle perturbation. Following a sudden increase in the amplitude of the sinusoidal stretching the TSR response adapted rapidly within one or two stretching cycles to its new steady state level. It did not increase, however, in proportion with the amplitude of stretch and therefore, the gain of the TSR decreased with increasing magnitude of stretch. In other words, there was a nonlinear relationship between the average amplitude of the TSR response and the average amplitude of the stretch perturbation.

A set of power spectral curves of elbow angle signals, IEMG (t1 = t2 = 0·03 s) signals, components of IEMG signals linearly related to elbow angle changes and remnant components of IEMG signals for five different amplitudes of elbow angle perturbation at a 20% contraction level are presented in fig 2. Sharp peaks were always present in the elbow angle spectra at the stretching frequency with negligible variance at harmonics of the stretching frequency indicating that the elbow angle perturbation was always a good approximation to a sinusoid. The frequency of the sinusoidal perturbation was not always exactly 4·0 Hz but was usually close to 4·0 Hz. Across all subjects the minimum and maximum stretching frequencies were 3·5 and 4·4 Hz, respectively, but the variation of stretching frequency between tests within any one

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**Fig 1.** Polygraph tracings of sinusoidal elbow angle perturbations and IEMG responses from a cerebral palsied subject voluntarily sustaining a contraction of 10% of a maximum contraction (top half of diagram) and 20% of a maximum contraction (lower half of diagram). The frequency of elbow angle perturbation was held constant at 4·0 Hz but the magnitude was increased from 1·67 through 2·5, 5·0, 7·5 to 10·0 degrees peak to peak (from left to right across diagram). The IEMG calibration marks indicate 0% and 30% of maximum contraction.
subject was always small (range 0.2-0.6 Hz) and has been ignored in the statistical analysis presented below.

As illustrated in fig 2, the IEMG power spectra always displayed a sharp peak at the stretching frequency. Indeed, the coherence at the stretching frequency was 80-98% indicating that this high percentage of the variance of the IEMG signal at the stretching frequency was linearly related to elbow angle changes. There was a relatively small amount of variance of the IEMG signal at other frequencies and as illustrated in fig 2, this variance was mostly at low frequencies less than about 3.0 Hz. As indicated by both the IEMG and remnant IEMG spectra (fig 2), the amount of variance of the IEMG signal at the first harmonic of the stretching frequency was a negligible proportion of the variance at the stretching frequency. This indicates that although the IEMG reflex response was "noisy", it had negligible harmonic distortion due to nonlinearities in TSR transmission and was a good approximation to a sinusoid even at the larger amplitudes of stretch.

Broad bandwidth spectral curves of elbow angle, IEMG, coherent component of IEMG and remnant IEMG signals for five different amplitudes of stretch at a 10% contraction level for one cerebral palsied subject are presented in fig 3. The IEMG signal presented in this analysis was derived from the short time constant (t1 = t2 = 0.008 s) filter. A large peak was always present in the IEMG spectra at the stretching frequency with a relatively small level of variance at other frequencies (fig 3). Because of the short time constants in the filter the remnant IEMG spectra displayed variance across a broad range of frequencies up to about 30.0 Hz (fig 3). Although there were peaks in the remnant IEMG spectra they were small relative to the peaks in the IEMG spectra at the stretching frequency. Furthermore, the relatively small peaks in the remnant IEMG spectra were inconsistent from run to run, only occasionally coincided with a harmonic of the stretching frequency and did not increase in magnitude as the amplitude of stretch was increased (fig 3). From these results it can be concluded that the short time
constant (0.008 s) IEMG signal provided a statistically "noisy" measure of TSR responses to sinusoidal stretch. Nevertheless, the responses contained negligible harmonic distortion and were a good approximation to a sinusoid even at the larger amplitudes of stretch.

Profiles of the mean gains for normal and cerebral palsied subject groups at different contraction levels and different magnitudes of elbow angle perturbation are presented in fig 4. The analysis of variance revealed no significant differences in the gains between normal and cerebral palsied subject groups. The gain increased significantly (p < 0.001) between 10% and 20% average contraction levels and the gain decreased significantly (p < 0.001) with increases in amplitude of elbow angle perturbation from 1.67 degrees through 10.0 degrees peak to peak. Phase seemed relatively insensitive to changes of either contraction level or magnitude of stretch and there were no significant differences in phase between any of the conditions or between the subject groups.

**Discussion**

Results of this study show that TSR gain increases with average contraction level and decreases with magnitude of stretch in both normal and cerebral palsied subjects. This illustrates the difficulty of obtaining objective measures of muscle tone. If one wishes to use measures of TSR gain to assess muscle tone then both contraction level and magnitude of stretch must be carefully controlled. This is particularly important when assessing reduction of spasticity following treatment since there is a tendency to increase the range of passive movement and to lower the frequency of displacement as the mechanical resistance of the limb decreases. Both of these effects will lower the measured gain of the TSR and will therefore cause any reduction of spasticity to be overestimated.

Although the influence of contraction level and magnitude of stretch on TSR transmission makes difficult the task of objectively measuring muscle tone during voluntary activity it nevertheless raises interesting questions about the underlying physiological processes. Why does the gain of the TSR decrease as the magnitude of stretch is increased? Almost certainly the initial answer to this question is that the linear range of stretch has been exceeded.
The problem with this explanation is that TSR can “reset” its gain in response to a stretch of large amplitude so that high gain for small perturbations can apply at the new limb position. Such a nonlinear resetting of gain in response to changes of amplitude of stretch has been described previously in the response of primary spindle endings. Indeed, Matthews and Stein commented that the nonlinearity presented certain puzzling features in view of the fact that the spindle response was still reasonably sinusoidal with little sign of harmonic distortion or change in phase. This is similar to the nonlinearity in the relationship between elbow angle perturbations and the IEMG reflex responses described in the present study. Although the resetting of TSR gain in response to a change in the magnitude of stretch might be a reflection of a similar nonlinearity in the response of primary spindle endings, the possibility that adaptive processes exist within the central nervous system which automatically adjust the gain of the TSR should not be discounted.

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