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OBSERVATIONS ON THE AUTOMATIC COMPENSATION OF REFLEX GAIN ON VARYING THE PRE-EXISTING LEVEL OF MOTOR DISCHARGE IN MAN

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SUMMARY

1. The human stretch reflex is well known to show 'automatic gain compensation'; in other words, the electromyographic (e.m.g.) response evoked by a given disturbance increases progressively with the level of pre-existing voluntary activity, and so remains an approximately constant proportion of the background.

2. Such behaviour has now been observed using vibration as the stimulus to Ia action and recording the reflexly developed force, in addition to the e.m.g. Inhibition was studied as well as excitation by vibrating the antagonist as well as the agonist, and found to be similarly regulated.

3. The experiments were performed on the elbow flexors while they were contracting isometrically under voluntary drive. The vibration was either square-wave modulated at 5 Hz or delivered in bursts of one to five pulses. The latency of the e.m.g. responses produced by the latter was sufficiently short to show that gain compensation was a feature of spinal reflex action.

4. In the Discussion, it is concluded that in principle 'automatic gain compensation' can be readily attributed to the known organization of the motoneurone pool. As the background force increases so does the number of active motoneurones available to be frequency-modulated by a given input, and the larger and stronger will be those motor units which are on the verge of recruitment or de-recruitment.

INTRODUCTION

Voluntary contraction is widely accepted as being under continuous reflex control by a variety of sensory receptors, including those in both agonists and antagonists. It might be thought that a given change in afferent firing would reflexly elicit the same absolute muscular response whatever the pre-existing level of motor output. In fact, on the basis of a variety of e.m.g. studies, autogenetic excitatory reflexes are well known to vary with the initial level of motor discharge. Their absolute size increases with the background level of activity so that they tend to remain an approximately constant proportion of the pre-existing level. The functional importance of this seems to have first been emphasized by Marsden, Merton & Morton (1972, 1976) who analysed such behaviour on interfering with the movement of the thumb and noted that such an 'automatic compensation of gain' would ensure that reflexes remained

'appropriate to the delicacy or otherwise of the task in hand', as well as compensating for fatigue. They studied the 'long-latency' component of the response evoked by displacement, which occurs sufficiently late to make transcortical mediation a possibility. They thus seem to have felt that gain compensation depended upon something more complex than the organization of the motoneurone pool. However, in subsequently re-appraising the situation Marsden, Rothwell & Day (1983) found similar gain compensation for the short-latency spinally-mediated component of the response, in agreement with the findings of a growing number of other workers in related situations (for example, Gottlieb, Agarwal & Stark, 1970; Joyce, Rack & Ross, 1974; Cooke & Eastman, 1977; Iles, 1977). The size of the H reflex has also long been known to increase with the level of background contraction (Paillard, 1955; Gottlieb & Agarwal, 1971). The simplest possibility is that gain control arises just because when more motoneurones are active, more are available to be influenced by any given afferent input.

The present experiments contribute in two respects to the assessment of the functional significance of gain compensation, without particularly exploring its mechanism. First, inhibitory reflex action from the antagonist, elicited by what are presumed to be Ia afferents, has been found also to possess automatic gain compensation. This was shown by exciting the afferents by applying vibration to the tendon of the antagonist, while varying the strength of voluntary contraction of the agonist. *A priori*, the inhibitory reflex might have been expected to decrease with increasing agonist contraction, rather than increasing, since the responsible interneurones are themselves then progressively inhibited by supraspinal action (Tanaka, 1974; Shindo, Harayama, Kondo, Yanagisawa & Tanaka, 1984). Similar compensation was noted in passing by Newsom Davis & Sears (1970) on studying the short-latency inhibitory action of sudden lung inflation on the electromyographic (e.m.g.) activity of human intercostal muscles. Secondly, the reflexly elicited changes in muscular force, whether due to excitation or inhibition, have been recorded in addition to the more usual e.m.g.s. For the elbow flexors gain compensation is equally prominent for this functionally more significant type of recording, thereby eliminating the possibility that the e.m.g. changes might have been regularly dominated by the responses of motor units which were already firing close to or above their fusion frequency, and so were associated with little or no mechanical effect. Such high rates of firing have, however, be observed for certain other muscles with quite moderate strengths of contraction (De Luca, LeFever, McCue & Xenakis, 1982), and this mechanism was invoked in two separate studies in which increases in the size of the H reflex with increaasing background contraction failed to lead to an increase in the size of the mechanical response (Paillard, 1955; Gottlieb & Agarwal, 1971). The present findings have already been published in preliminary form (Matthews, 1982*a*, *b*).

METHODS

The experiments were performed on normal adult subjects of either sex. Seven were studied altogether, six of whom were tested in the first set of experiments, and five in the second set. In all cases the subject exerted a steady degree of elbow flexion and the reflex effects of vibrating either

biceps or triceps were studied. The methods are given in outline only since most of them have already been described elsewhere (Cussons, Matthews & Muir, 1980; Matthews & Muir, 1980; Matthews & Watson, 1981; Matthews, 1984*a*).

The subject sat with his elbow supported and with his forearm running vertically upwards in full supination. The front of the wrist pulled against a metal harness which was connected to an isometric force transducer. The subject's task was to maintain an approximately steady force at the wrist by keeping an oscilloscopic display of force at a predetermined level. Usually the signal was low-pass filtered to remove the small changes of force reflexly elicited by the vibratory stimuli. The subject maintained the contraction for 34 s, during which the stimuli were applied repetitively; he then rested for 24 s, after which the cycle was repeated. The first 7 s of recording from the beginning of the contraction were discarded and the responses from the ensuing 26 s or so averaged. This was done for a range of forces, the greatest being 100 N at the wrist which was the largest the subjects could maintain comfortably for the requisite time; it represents well below 50% of the maximum voluntary contraction (m.v.c.). The response at a given intermediate level of force was normally determined both before and after using the largest forces.

Vibration

Two different vibrators were used with their attendant control circuitry. The first was a standard mains-driven physiotherapy vibrator (Pifco, 1556) which was simply pressed against the subject's arm by the experimenter. This oscillated at 100 Hz with a peak-to-peak movement of about 0·5 mm. It was automatically turned on and off at a preset repeat frequency (usually 5 Hz), always at the same phase of the vibration cycle, to give square-wave modulated vibration; the precise wave form of the movement was not, however, known. The second was a conventional laboratory vibrator (Goodman, V47) driven electronically and with a length transducer permanently attached to its shaft. It was run open-loop, without servo control, and its input signal was adjusted to ensure a suitable wave form of movement, especially at the beginning and end of vibration. A train of one to six unidirectional mechanical pulses was used, each lasting just under 7 ms, at a frequency of 140–150 Hz. These brief periods of vibration were repeated at 2·5 Hz. The driving signal responsible for each individual pulse of vibration consisted of two to three square waves of differing polarity. The small vibrator was mounted on a pivoted arm to allow it to be applied to the arm with a constant pressure; this was counterbalanced by weights, and damped by a dash-pot.

Recording and analysis

All data were recorded for subsequent analysis on a seven channel FM tape recorder together with various signal markers. The force signal was recorded on two separate channels; once at low gain, and once at high gain after automatically backing off the steady level at the beginning of the contraction so as to avoid saturation. The high gain signal was the one used for analysis; it was always high-pass filtered (cut-off, 50 Hz) to reduce a small signal component at the frequency of the vibration, apparently due to a direct mechanical effect. Additional filtering (cut-off, 17 Hz) was employed before averaging the responses to square-wave modulated vibration, since the artifacts were then partly superimposed upon the desired physiological responses. In the illustrations of these (Figs. 1 and 2) the time lag introduced by both sets of filtering has been corrected for by shifting the force records by the amount appropriate for the fundamental. The records for the brief periods of vibration have not been shifted, but control recordings without the 50 Hz filter showed they were delayed by about 3 ms.

The e.m.g. of biceps, and occasionally of triceps and of brachialis and brachioradialis, was recorded with surface electrodes (bandpass, 10 Hz–1·25 kHz). For biceps, triceps and brachioradialis the electrodes were placed approximately 5 cm apart over the belly of the muscle half-way up the arm. For brachialis the electrodes were more closely spaced and were placed on the medial side of the arm much closer to the elbow and just below the belly of biceps. For subsequent analysis the e.m.g. was usually full-wave rectified, after slightly 'smoothing' it by integrating its value over the short period between the successive samples taken by the averager (always below 2 ms). Both electrical and mechanical responses were averaged for 64–512 cycles of stimulation using a small hard-wired averager (NL 750, Digitimer) and employing bin widths of 0·42–2 ms. The output of the averager was displayed on a digital oscilloscope from which it could be plotted.

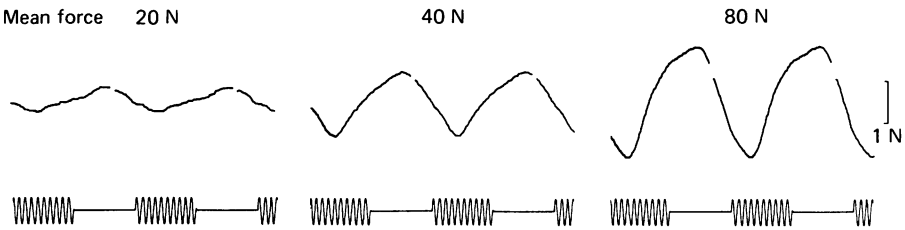

Fig. 1. The effect of increasing the mean strength of contraction of the elbow flexors on the rhythmic variation of force reflexly elicited by vibrating biceps (automatic gain compensation). The bottom records show the voltage applied to the physiotherapy vibrator to produce the square-wave modulated vibration (100 Hz modulated at 5 Hz); the precise wave form of the vibratory movement was unknown. The middle records show the resultant modulation of force on a high gain for mean forces of 20, 40 and 80 N; 128 individual cycles of response were averaged in every case. For ease of inspection each average has been plotted out repetitively on a linear sweep, with the replays in immediate succession with the correct time relation, to give a better impression of a continuing cyclic response (the small gap corresponds to the short segment that was not averaged). The force records have been shifted slightly to the left relative to the vibration marker to allow for a lag introduced by filtering.

RESULTS

The first set of experiments concentrated upon mechanical recording and made use of a hand-held physiotherapy vibrator. This sufficed to demonstrate the regular occurrence of automatic gain compensation for the reflex effects of vibration, as illustrated in Fig. 1 which is typical of the six subjects studied. It shows the change in the force developed by the elbow flexors, recorded at the wrist, on applying the vibrator to the tendon of biceps and turning it on and off at regular intervals; the repeat rate of such square-wave modulated vibration was 5 Hz and the vibration frequency itself was 100 Hz. The considerable variability between successive individual responses has been eliminated by averaging. Rhythmic reflex responses to sinusoidally-modulated vibration have already been described (Matthews & Muir, 1979; Cussons, Matthews & Muir, 1980; Muir, Popp & Rath, 1981). The new feature illustrated here is that the absolute size of the response increased progressively as the subject increased the background level of voluntary contraction. However, in relative terms the force modulation remained approximately constant at about 3% of the mean value of the voluntary contraction; the records are arranged so that their mean levels are aligned, with their differing mean values indicated above. Intermediate responses were obtained on using intermediate levels of background force. The subject was making no attempt to respond voluntarily to the rhythmic stimulus, which in any case was probably too rapid for him to do so. The responses may thus be considered to be reflex and so provide a clear example of automatic gain compensation; similar compensation was observed on testing all subjects in this way over a similar range of background forces. The reflex response is presumed to depend primarily upon a regularly varying excitation of the Ia afferents in the vibrated biceps, though other afferents may also have influenced it. With this type of stimulation and recording there is little point in attempting to specify the precise reflex paths involved; however, the latency seems reasonably appropriate for Ia mono- or oligo-synaptic autogenetic excitatory action to be chiefly responsible.

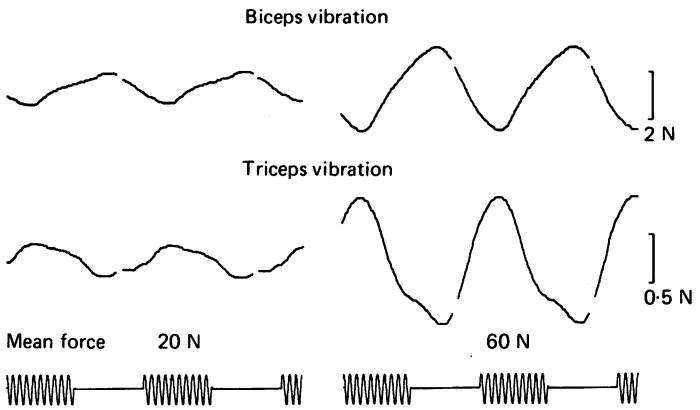

Fig. 2. Comparison of the effects of vibration of biceps and of triceps in producing modulation of a flexor contraction. The mean force of contraction is shown below. Averaging and display as in Fig. 1, but for a different subject. Further results from the present subject (A.J.P.) are shown in Figs. 3–7.

Compensation of inhibitory action

Similar automatic compensation of reflex gain was observed in all six subjects tested on studying the inhibitory modulation of the level of biceps contraction produced by vibrating its antagonist triceps. Fig. 2 compares the effect of vibrating triceps with that of vibrating biceps itself for two different levels of flexor contraction. It can be seen that the responses differ in phase by approximately 180° in their relation to the timing of the vibratory stimulus. This shows that the rather smaller triceps effect depends upon inhibitory reflex action, probably reciprocal I a inhibition, and not upon any excitation evoked by spread of vibration to the contracting flexors. Similar results were obtained when the modulation frequency was reduced. Triceps itself remained flaccid during its vibration and so could not be held responsible for directly producing the observed modulation of the force recorded at the wrist.

The possibility that a weak rhythmic contraction of triceps might have been missed on simple inspection was excluded in four of the subjects by recording electromyographically from triceps. The resulting record was compared with those obtained with triceps vibration when triceps, rather than biceps, was contracting under various levels of voluntary drive. The apparatus was re-arranged to permit the subject to maintain a steady extension force, and the mechanical responses were broadly like those in Fig. 1. If the responses during biceps contraction had been due to rhythmic activity of triceps instead of biceps, then the e.m.g. modulation should have been much the same as when a similar modulation of force, genuinely attributable to triceps activation, was produced by vibrating the contracting triceps. But no appreciable modulation was seen on recording from triceps during biceps contraction using the amplification required to display it when triceps was contracting; in both cases the triceps e.m.g. was similarly rectified and averaged.

It may be noted further that the rectified e.m.g. recorded from the contracting muscle, whether biceps or triceps, was always deeply modulated with a constant phase relation to the square-wave modulation of the vibration (cf. Fig. 1, Matthews & Muir, 1979). This argues that the rhythmic variations in the recorded force were indeed

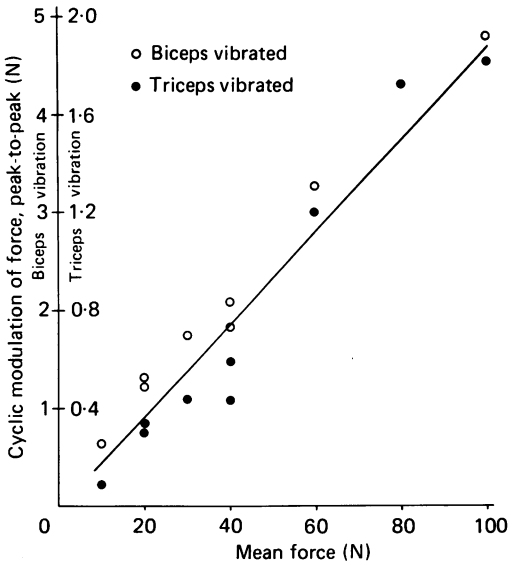

Fig. 3. The relation between the depth of modulation of flexor contraction and the mean strength of the contraction, found on vibrating either biceps (○) or triceps (●) in the experiment of Fig. 2. Note the difference in the scaling of the ordinate for the two types of response.

reflexly elicited, rather than being due to a direct mechanical effect of the stimulation itself. Moreover, it is very difficult to see how any such direct effect could vary so greatly in magnitude with the level of contraction.

Fig. 3 shows graphically the increase in the depth of the modulation of force with increase in the background level of flexor force for the experiment of Fig. 2. On average the inhibitory reflex was only some 40 % of the excitatory reflex, as was usual (range 20–45 %), but both increased similarly, and approximately linearly, with the background. The peak-to-peak modulation has been measured in each case, in spite of the slightly different wave forms involved; no attempt has been made to analyse these further, or to attempt to isolate any different components of response (the precise wave form varied with the mean force and with the subject). The observations from this type of experiment sufficed to show that automatic gain compensation occurred for inhibition much as for excitation, without prejudice as to precise reflex pathways involved. However, it is not claimed for either that the compensation is invariably perfect, in the sense of maintaining the proportional value of the response quite constant, or that the regulation is always quantitatively identical for excitation and inhibition, though this was commonly so. Moreover, it should be emphasized that only relatively low forces have been studied (below 50 % m.v.c.). One of the six subjects ceased to show gain compensation of both the excitatory and the inhibitory responses, which then remained of constant absolute size, for forces in the range 60–100 N; the responses of another subject failed to continue increasing when the background force was raised from 80–100 N. This raises the possibility that all would have shown such 'saturation' if larger initial forces had also been studied (cf. Joyce & Rack, 1974).

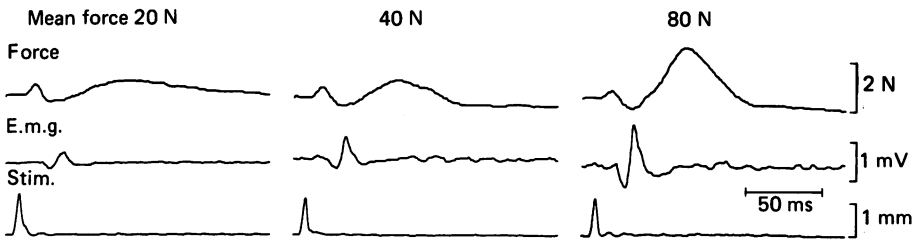

Fig. 4. 'Automatic gain compensation' seen for both the electrical and mechanical recordings of the tendon jerk response elicited by a single pulse of vibration applied to biceps tendon. Top, the force developed at the wrist displayed on a high gain. Middle, the unrectified electromyogram (e.m.g.) recorded from biceps. Bottom, the wave form of the mechanical stimulus (stim.) recorded from a transducer attached to the vibrator. Sixty-four responses averaged; stimulus repeated at 2·5 Hz.

Response to brief inputs

The second set of experiments employed single or short trains of vibratory pulses, delivered from an electronically controlled vibrator, to produce better temporal resolution and so permit firmer conclusions to be drawn about the nature of the reflex responses being studied. The e.m.g. was then routinely analysed as well as the mechanical recordings. All but one of the subsequent illustrations are derived from a single subject, that of Figs. 2 and 3 (A.J.P.), so as to ensure comparability; his behaviour was entirely typical.

Excitation. Fig. 4 shows the response of biceps to a single brief tap to its tendon for three different levels of background contraction. The unrectified e.m.g. shown in the middle has a latency of below 20 ms and can confidently be attributed to Ia short-latency spinal action. As to be expected from previous work it increases with the amount of initial muscle activity. The force developed in this 'tendon jerk' response is shown above and can likewise be seen to increase progressively; it is preceded by a small mechanical artifact of approximately constant size. Fig. 5 shows that both the electrical and the mechanical aspects of the reflex response increase approximately linearly with the background force.

Automatic gain compensation in the qualitative sense was invariably seen in all subjects for the mechanical as well as the electrical response using one to five successive brief taps at 150 Hz as the stimulus. This was equally so when the e.m.g. was rectified before averaging and the peak response measured. The mechanical responses normally showed less variation on repeated trials. But though the responses increased progressively with the background the best-fit line sometimes passed appreciably above the origin, which is to say no more than a tendon jerk type of response would still be expected when the muscle was not contracting; this was not tested directly since with the present arrangements it was not readily feasible to do so. When this occurs, however, gain compensation cannot, of course, be expected to maintain the size of the response in relation to the background at an absolutely constant value.

Inhibition. During steady flexor contraction a brief train of vibratory pulses to triceps produced a momentary inhibitory reduction of the force developed. As illustrated in Fig. 6 (top) the absolute change in force produced by a given stimulus

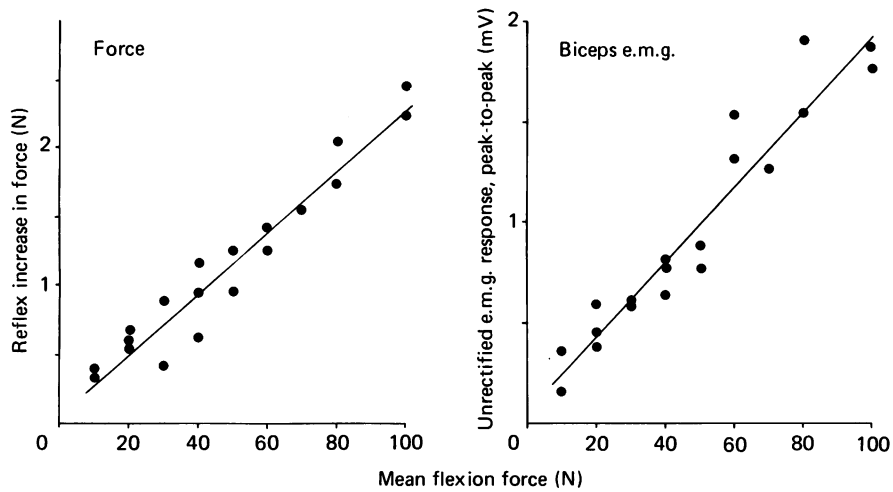

Fig. 5. The relation between the sizes of both the electrical and mechanical responses elicited by a single tap, and the level of pre-existing voluntary flexor contraction. Same experiment as Fig. 4.

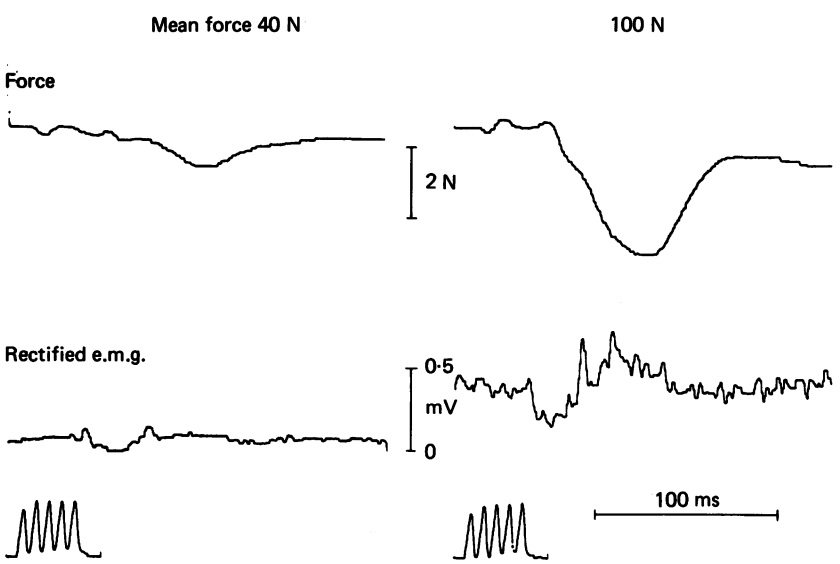

Fig. 6. The inhibitory effect on biceps produced by five pulses of vibration to triceps seen at two different levels of flexor contraction. Top, mechanical responses on a high gain. Middle, the rectified e.m.g. from biceps. Bottom, the stimulus wave form; peak displacement approximately 1 mm. 128 responses averaged. Stimuli repeated at 2·5 Hz.

was larger when the background force was increased. The rectified e.m.g. from biceps (middle) also showed a brief reduction; this was slightly in advance of the mechanical transient and so may equally be taken as representing the inhibitory response. The absolute value, in mV, of this inhibition of the e.m.g. likewise increased with the background force.

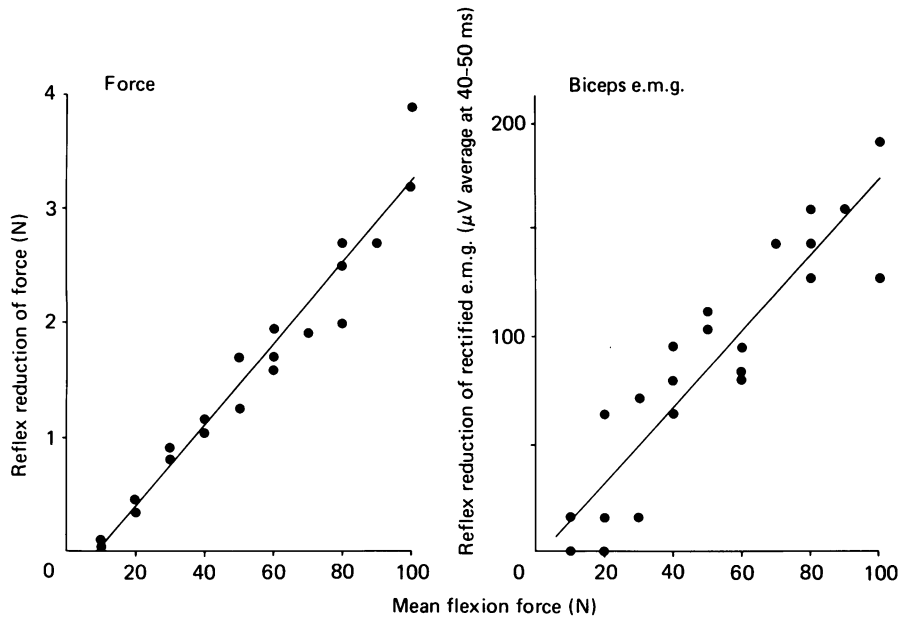

Fig. 7. The relation between the sizes of the inhibitory flexor responses, both electrical and mechanical, and the level of flexor contraction on vibrating triceps with five pulses. Same experiment as Fig. 6.

Fuller results from the same experiment are shown graphically in Fig. 7. The automatic compensation of the gain of the inhibitory effect of triceps vibration can be seen to be highly effective, with the sizes of both the electrical and mechanical responses being nearly directly proportional to the background force. Similar results were obtained in the five other experiments, using from one to five pulses to triceps. It is particularly worth noting that the points in graphs like those of Fig. 7 regularly seemed best fitted by a straight line rather than by a curve, including one with a progressively decreasing slope; the latter shape would probably be expected if there were a powerful descending inhibition of the relevant interneurones that increased with the level of voluntary contraction (see Discussion). In contrast, the excitatory response elicited by vibrating biceps with a short train of pulses sometimes showed a tendency to saturate for mean forces of 60–100 N in both the electrical and mechanical recordings. This may have been related to their being larger than the inhibitory responses and again indicates that there are probably limits to the potency of gain compensation (cf. p. 78) and that it seems likely to operate most effectively for small reflexes superimposed upon weak to moderate pre-existing contractions.

In line with the above it was found that the inhibitory reduction in the rectified e.m.g. was normally a constant proportion of the initial background level; the steady-state levels of force and e.m.g. are well-known to be approximately linearly related (cf. Lippold, 1952). The only exception was the experiment of Fig. 6 for which the percentage reduction was slightly greater for the smaller background forces, while becoming approximately constant for forces of 60 N and above.

Latency. The latency of the inhibitory response seen in the biceps e.m.g.s of Fig. 6

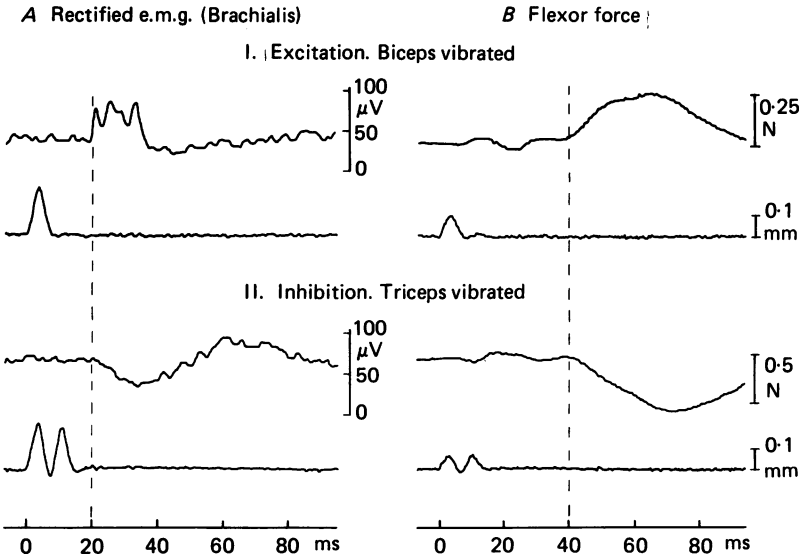

Fig. 8. Comparison of the minimum latency for inhibition (below) with that for excitation (above). These prove to be very similar whether observed in the rectified e.m.g. (*A*, left), or in the recording of force (*B*, right). In this subject (P.B.C.M.) on recording from brachialis there is no sign of the initial excitation seen in most subjects on recording from biceps. The e.m.g. and force recordings were obtained on different occasions using different sized stimuli. The mean flexor force was 50 N except for the bottom left record for which it was 60 N. 128/256 responses averaged; stimuli repeated at 2·5 Hz.

is 34 ms, measured from the beginning of the stimulus train. This is relatively long in relation to the excitation of biceps seen in Fig. 4. This might have been partly because a certain amount of interneuronal facilitation was required before an appreciable effect could manifest itself, so that the latency might perhaps have been more appropriately measured from one of the later pulses rather than the first. The inhibitory response in biceps e.m.g. in response to a single pulse to triceps was normally almost undetectable in the face of the background noise, although a mechanical response was seen; several pulses elicited a clear effect in both types of recording. However, the initial part of the inhibitory response seems more likely to have been obscured by a small concurrent excitation. A hint of such an effect can be seen in the e.m.g.s of Fig. 6; in some other subjects an initial excitation was indubitably present, and was seen equally on averaging the e.m.g. without rectifying it. Its origin is uncertain, but spread of vibration to the muscle contracting provides the most likely possibility; alternatively, other reflex pathways may have been involved such as Ib excitation from the antagonist.

To study the matter further, e.m.g. recordings were also taken in three subjects from the two other flexors of the elbow, namely brachialis and brachioradialis; their mechanical responses must have been contributing to the observed changes in flexor force. For these two muscles, there was appreciably less sign of an initial excitation, as illustrated in Fig. 8 from the subject giving the clearest findings. The left-hand records show the e.m.g. recorded from brachialis in response either to a single tap to biceps (above) or to two closely spaced such mechanical pulses to triceps (below).

The latencies of the two responses are virtually the same (just on 20 ms) and there is no sign of an initial excitation preceding the inhibitory response. The lengths of the conduction pathways involved are not, of course, quite identical so it is not possible to compare the precise synaptic delays involved in the two cases; but the records fit well with the view that the inhibitory responses depend upon Ia reciprocal action, involving a single interneurone. Two pulses were used to elicit the inhibition since this produced a more obvious effect by virtue of its lasting longer; a similarly early response was seen when a single pulse was used, but the overall response was then less visually convincing by being much closer to the background noise level.

The right-hand records in Fig. 8 show the mechanical responses obtained from the same subject on using similar but smaller-amplitude stimuli on another occasion. The small stimuli were used in order to reduce the size of the initial mechanical artifact which outlasted the duration of the stimuli themselves by virtue of the arm continuing to oscillate, presumably at its resonant frequency. The subsequent quite distinct and much larger reflex response can be seen occurring with a latency of close to 40 ms, both for excitation (above) and for inhibition (below). The excitation can be confidently ascribed to monosynaptic action showing that the inhibition must have acted via a central pathway with a comparable latency, thus supporting the findings with electrical recording. It is concluded, in line with initial expectation, that the inhibitory action currently studied is likely to depend predominantly upon Ia di- or tri-synaptic reciprocal (direct) inhibition; but, of course, contributions from other pathways are not excluded.

Absence of response from triceps. Control e.m.g. recordings were made in three subjects from triceps when it was being stimulated by a brief train of mechanical pulses during flexor contraction. This again showed that triceps remained inactive and so could not have been contributing mechanically to the observed reflex responses (cf. p. 77). With the relatively wide separation of the electrodes on triceps (approximately 5 cm) some pick-up of the electrical activity of the flexors would be expected and was seen. This was recognized as such by virtue of its showing the typical flexor pattern of response of a steady initial level of discharge which was partially inhibited on triceps vibration (cf. Figs. 6 and 8). The mean level of activity, in mV, was about $\frac{1}{5}$ of that recorded during the same contraction from electrodes placed directly over a flexor muscle. When triceps was made to contract by the subject exerting force in the extensor rather than the flexor direction the background e.m.g. level rose very considerably and a typical large excitatory response was obtained on vibrating triceps with a brief train or single pulse. The mechanical changes associated with these obvious excitatory responses were, however, no larger than those evoked by similar vibration applied to triceps when the flexors were contracting; these latter can thus be confidently attributed to inhibition of the ongoing flexor contraction, rather than to a brief period of extensor co-contraction, since on the above showing significant excitation of triceps could not have been missed in the e.m.g.

DISCUSSION

The present experiments provide two further examples of the automatic compensation of the gain of a reflex in accordance with the background level of motor firing: tendon vibration provided the stimulus and presumably acted by exciting the Ia afferents. They extend previous work on the limbs by demonstrating the effect for an inhibitory reflex, as well as for an excitatory one, thereby showing that a relatively weak inhibition can remain functionally effective in the face of a greatly increasing excitation of the motoneurone pool, rather than being overwhelmed by it. In addition, for both excitation and inhibition, the effect has now been shown for the mechanical response also, and not just for the e.m.g. with its possible limitations (see also Joyce *et al.* 1974). However, there may be other situations where such efficient regulation does not occur, such as when the initial contraction is strong enough to involve most of the motoneurones to the muscle studied and to cause them to fire at a rate close to their tetanic fusion frequency. Different muscles seem likely to differ in their behaviour in this respect (De Luca *et al.* 1982). In the present experiments on the elbow flexors the contraction has always been appreciably below half-maximal and in some subjects the mechanical response has appeared to 'saturate' for the larger values used. Gain compensation may be suspected to operate most efficiently when neither the background contraction nor the reflex regulated are particularly large.

As yet, automatic gain regulation only seems to have been observed in situations in which the level of motoneurone firing has been varied by altering the voluntary drive, and with the reflex examined being one elicited by muscle proprioceptors; this holds also for complex responses such as the 'grab reflex' (Traub, Rothwell & Marsden, 1980). However, as outlined below, consideration of the likely mechanisms of gain compensation suggests that the currently available examples are unlikely to be unique, though not all reflexes need be so controlled. The fact that gain compensation was seen for the inhibitor action produced by vibrating the flaccid antagonist argues that the effect arises centrally, rather than being due to an increased spindle response to a given stimulus as could have been the case for experiments involving gross muscle stretch. Spindles in the agonist might well be progressively sensitized by fusimotor action, but those in the antagonist should have given the same response to vibration irrespective of the level of contraction of the agonist since a non-contracting muscle normally lacks all fusimotor drive (cf. Burke, 1981). This all agrees with the observation that a given burst of spindle discharge, produced by stretch and recorded microneurographically, may elicit a reflex response when a muscle is contracting while failing to do so when it is relaxed (Burke, Hagbarth & Löfstedt, 1978). In addition, gain compensation may be seen for certain e.m.g. responses elicited by electrical stimulation (cf. Iles, 1977). Thus at least some degree of 'automatic gain compensation' seems likely to be a widely applicable principal of motor control.

Functional significance

The recognition of a continuous compensation of reflex gain in accordance with the level of contraction goes far beyond the long-accepted idea that the excitability of the motoneurones of a non-contracting muscle may be too low for them to respond at all to a given excitatory input. This specific case retains its importance, of course,

as for example in helping to ensure that during limb movement the passive stretching of the antagonist by the action of the agonist fails to evoke a stretch reflex from it (inhibition by descending pathways will presumably also then be involved). The advantages to be gained from continuously adjusting excitatory reflexes with the level of background contraction have already been fully recognized (Marsden *et al.* 1972, 1976). The ability of inhibitory reflexes to operate effectively at all levels of muscular contraction would seem at least as dependent upon such regulation. Without automatic gain compensation, regulatory reflexes, whether excitatory or inhibitory, would tend to be too mechanically powerful when pre-existing muscle contraction was weak, and too feeble when muscle contraction was strong. This would seem to apply equally when the strength of muscle contraction is being modulated phasically, as in walking, although associated changes in the excitability of various interneurones might then tend to submerge the effect. In addition, when the neural drive to a fatigued or otherwise weakened muscle has to be increased so as to maintain the mechanical effects of voluntary muscle action, then any reflex modulation of this will be preserved at its normal level.

Contributory mechanisms

Since automatic gain compensation can be seen with the simplest of spinal reflexes it is appropriate to outline how such behaviour need depend upon no more than well-known properties of the motoneurone pool. Such discussion emphasizes, as many have appreciated (cf. Stein, 1974), that there is no necessity to invoke an elaborate supraspinal mechanism to achieve this end as seems sometimes to have been felt. All the motoneurones of a given muscle can be expected to be influenced by a given reflex, though not necessarily to the same degree, irrespective of whether or not they happen to be discharging initially. An excitatory reflex will somewhat increase the firing frequency of those that are already active, and recruit a certain number of those that are initially silent; conversely, an inhibitory reflex will silence some that are initially active and reduce the firing rate of the remainder. The strength of the consequent muscular response will depend upon both mechanisms (i.e. frequency modulation and recruitment) so the question is, how will the reflexly-elicited change in each of these vary with the level of activation of the motoneurone pool, assuming that the pool continues to receive a constant reflex input (i.e. that there is no change in either the afferent input or in the excitability of any interneurones involved). However, the present discussion makes no attempt to cover situations for which a given afferent input exerts qualitatively different effects on different sized motoneurones supplying the same muscle. Such behaviour, with a shift from inhibition of slow motoneurones to excitation of fast motoneurones by electrically-evoked cutaneous afferent volleys, has now been seen in conscious man (Datta & Stephens, 1981) as well as in the anaesthetized cat (Burke, Jankowska & ten Bruggencate, 1970).

Frequency modulation. For modulation of firing the answer seems clear. Considering first the behaviour of any individual motoneurone, a given synaptic input will, if anything, be expected to produce a larger change in firing frequency as the pre-existing discharge rate increases, since this is the way motoneurones behave in response to constant current excitation as they move from their 'primary' to their 'secondary' range (Kernell, 1965). Secondly, considering the population as a whole, the greater

the number of motoneurones that are discharging the greater will be the change in the over-all amount of e.m.g. activity, since the frequency modulation of each individual motoneurone will contribute its quantum to the summed response. Thus whenever a reflex involves frequency modulation, then some degree of gain compensation can be expected to be seen in surface e.m.g.s for inhibitory as well as excitatory action. As already noted, the extent to which this will be reflected in the functionally more significant mechanical recordings will depend upon the distribution of initial firing frequencies of the units involved, in relation to their tetanic fusion frequencies.

The same considerations apply to that portion of the initial e.m.g. response, at the onset of a period of reflex excitation, that originates from motoneurones which are already active. As discussed elsewhere (Matthews, 1984*b*) this can be looked upon as the first sign of frequency modulation, with all those motoneurones that are already near the point of firing being activated in near synchrony to give a phasic response rising far above the subsequent maintained level. It follows that the same conclusions apply to the activation of discharging motoneurones by a brief period of reflex excitation, as in many of the present experiments. A brief inhibitory input can equally be expected to have an effect that varies with the pre-existing level of discharge.

Recruitment. The situation is more complex for the recruitment evoked by excitation, and likewise for the de-recruitment produced by inhibition. What happens will depend upon three separate variables, which are potentially independent but in practice normally seem to be linked. These are the distribution of the thresholds of different motor units, the distribution of their sizes (affecting both strength and unitary e.m.g. magnitude), and the distribution of the synaptic drive to different motoneurones for the particular reflex in question. For certain combinations of these variables gain compensation would not occur, and the degree of recruitment would remain constant whatever the initial level of activation of the motoneuronal pool. Moreover, if the reflexly-evoked synaptic drive decreases with motoneurone size, as happens for the Ia monosynaptic reflex, then the reflex response might conceivably get smaller with increasing initial activation of the motoneurone pool. Thus unlike the situation with frequency modulation, the role of recruitment in gain compensation can only be decided upon in the light of detailed knowledge of the particular situation involved.

Fortunately, the related case of recruitment for the cat's medial gastrocnemius has recently been analysed by Harrison & Taylor (1981) on the basis of their own measurements on a number of motoneurones. For each of these they determined the size of the Ia-evoked e.p.s.p. and the strength of the contraction elicited by its stimulation; as expected these varied inversely. This enabled them to deduce the behaviour to be expected from the motoneurone pool as a whole, on the assumption that all motoneurones had the same threshold depolarization; reasonable experimental support for this assumption has since been obtained (Pinter, Curtis & Hosko, 1983). Harrison and Taylor concluded that 'the gain of the Ia mediated stretch reflex should be approximately proportional to the developed force' when the background level of activity is varied by depolarizing all motoneurones equally. In present terminology this is to say that recruitment can reasonably be expected to lead to efficient gain

compensation of Ia-evoked reflex action, provided the increased initial motor discharge produced by voluntary action is due to some other, non-Ia, input that produces an equal effect on all motoneurones. In contrast, an excitatory reflex which, unlike Ia action, produced the same depolarization of all motoneurones irrespective of their size could be expected to elicit a response which became proportionately much larger as the background level increased, rather than remaining an approximately constant proportion as with the stretch reflex; enough steady Ia activity was assumed to be present to ensure that the motoneurones still continued to be recruited in order of size, which in their model was attributed entirely to their differing amount of background Ia-evoked depolarization. For both types of input the increase in the absolute size of the reflex with background activity occurred because the large motor units, responsible for marked force development, were relatively easily recruited by virtue of having the same threshold depolarization as the small ones. If their Ia-evoked depolarization had been even smaller in relation to that of the small motoneurones the effect for the stretch reflex would have been reduced or even abolished. The quantitative predictions of the model, particularly with regard to the precision of gain compensation, also depend crucially upon the finding that the size distribution of motor units is such that on recruiting them in order of increasing strength each new motor unit adds a constant fraction to the pre-existing force; this was first noted by Henneman & Olson (1965) when discussing the functional significance of the then newly-promulgated size principle.

The fact that the present findings for presumed Ia excitatory effects tally so well with those predicted by Harrison and Taylor suggest that at least some human motoneurone pools are organized similarly to that of medial gastrocnemius in the cat, and that recruitment contributes to gain compensation in man. Different types of reflex need not, however, behave in a quantitatively identical manner since they might differ in the distribution of their effects on different sized motoneurones. Thus, in general, both frequency modulation and recruitment can be expected to be associated with a degree of gain compensation, with the absolute size of any reflex increasing with the background. But whether or not the response will normally be a strictly constant proportion of the background cannot be decided upon.

It may further be noted that the same factors should operate to determine the efficacy of a constant excitatory volley descending upon the motoneurones from a higher centre. This too can be expected to lead to a response showing spinally-mediated 'automatic gain compensation', or even greater absolute enhancement, on increasing the level of pre-existing motoneuronal activity. No further explanation is thus necessarily required for the striking finding that ongoing voluntary contraction greatly potentiates the response to a single shock to the motor cortex delivered extracranially in conscious man (Merton & Morton, 1970; Merton, Hill, Morton & Marsden, 1982).

Inhibition

The inhibitory effects produced in the present experiments by vibrating the antagonist behaved in a similar manner to the excitatory effects of vibrating the agonist; their absolute size was, however, rather smaller. In one respect this occasions no surprise since they may also be presumed to depend upon Ia activation, and the

distribution of Ia inhibition to different sized motoneurones is well known to be the same as that for Ia excitation, with the small motoneurones again being preferentially affected (Burke, Rymer & Walsh, 1976). Thus the above arguments and Harrison and Taylor's conclusions apply equally to Ia inhibition. The short latency of the present inhibition of the e.m.g. shows it to be due at least in part to conventional 'reciprocal' Ia inhibition, whether or not more complex pathways are also involved in mediating its later components.

In another respect, however, it is surprising that the inhibitory effects were so well preserved with increasing contraction of the agonist, since this normally seems to be associated with an increasing inhibition of the inhibitory interneurones through which the Ia reciprocal inhibition is mediated. This was first found in the leg on studying the effect of peroneal nerve stimulation on the H reflex (Tanaka, 1974; Shindo *et al.* 1984) and has recently been similarly demonstrated for flexor muscles of the forearm (Day, Marsden, Obeso & Rothwell, 1984). In the leg, the reciprocal inhibition evoked by a single shock or brief trains was often totally blocked during quite weak voluntary contraction of the muscles being inhibited, but in the forearm an appreciable quantity of inhibition persisted throughout the considerable range of forces studied. Thus the present observation of the simple occurrence of what is supposed to be Ia inhibition of a voluntarily contracting muscle calls for no special comment, since it is already clear that in this respect the findings for the lower limb cannot be transferred to the upper limb.

However, in both of the previous situations a reduction of Ia inhibition was found on increasing the strength of the voluntary contraction of the muscle being inhibited. This should oppose the factors, discussed above, making for gain compensation and so gain compensation might be expected to be less effective for Ia inhibition than for Ia excitation, since this latter may be presumed to be primarily dependent upon monosynaptic action. Yet no obvious difference has been seen (compare Figs. 3, 5 and 7). The absolute size of both types of response increased approximately linearly with the background force, and, in particular, there seemed to be no special tendency for the inhibitory responses to fail to increase proportionately at the higher forces as might have been expected if the relevant interneurones were themselves being progressively inhibited. Perhaps the effect has simply been lost in the background noise through being comparatively modest like that for the forearm muscles (Day *et al.* 1984); the greatest change in the responsiveness of the interneurones seems to occur between contraction and relaxation rather than with gradations in the strength of contraction. Alternatively, some other unrecognized factor may have acted to submerge it, or some other pathway that is relatively unaffected by descending influences may be responsible for a significant part of the presently observed inhibitory effects.

But even though interneuronal effects have not been obvious in the present experiments the extent of automatic gain compensation of any polysynaptic reflex, whether excitatory or inhibitory, must depend upon whether the influence which sets the background level of motor discharge also affects the excitability of the relevant interneurones. For voluntary contraction, therefore, gain control may perhaps depend upon the 'effort' exerted as well as upon the actual level of motor discharge, in so far as these can be separated. It will be of some interest to compare the extent of automatic gain compensation for various types of reflex, in addition to the

proprioceptive ones hitherto studied, and with the background firing initiated in different ways. Moreover, a variety of muscles could usefully be studied over a wider range of background forces.

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