THE FIRING RATES OF HUMAN MOTONEURONES VOLUNTARILY ACTIVATED IN THE ABSENCE OF MUSCLE AFFERENT FEEDBACK

By V. G. MACEFIELD*, S. C. GANDEVIA†, B. BIGLAND-RITCHIE‡, R. B. GORMAN AND DAVID BURKE

From the Department of Clinical Neurophysiology, the Prince Henry Hospital and Prince of Wales Medical Research Institute, University of New South Wales, Sydney, Australia

SUMMARY

1. To quantify the net influence of muscle afferent feedback on the firing rates of human motoneurones, the discharge frequencies of single motor axons in the common peroneal nerve were recorded during sustained voluntary efforts performed in the absence of feedback from the target muscle. These data were compared with the firing rates of single motor units in the intact tibialis anterior muscle. In five subjects, recordings were made from fifty-two motor axons innervating tibialis anterior during acute deafferentation and paralysis of the dorsiflexor muscles produced by anaesthetic block of the nerve distal to the recording site.

2. Maximal sustainable firing rates were determined for twenty-four motoneurones, twelve of which were classified as relatively low threshold (estimated recruitment level $\leq 10\%$ maximal) and six as high threshold. Mean firing rates of the low-threshold motoneurones ($21 \cdot 7 \pm 2 \cdot 7$ Hz; $\pm$s.e.m.) were significantly higher than those of the high-threshold motoneurones ($14 \cdot 0 \pm 4 \cdot 4$ Hz). The mean firing rate of the twenty-four deafferented motoneurones during maximal efforts to contract the paralysed muscle was $18 \cdot 6 \pm 1 \cdot 9$ Hz, significantly lower than the maximal firing rates of single motor units recorded from the normally innervated tibialis anterior muscle ($28 \cdot 2 \pm 0 \cdot 6$ Hz).

3. During half-maximal efforts, the mean firing rate of eight deafferented motoneurones ($10 \cdot 8 \pm 1 \cdot 1$ Hz) was significantly lower than that of intact motor units ($16 \cdot 5 \pm 0 \cdot 2$ Hz). A similar finding was apparent during minimal efforts; the mean discharge frequency of seven deafferented motoneurones during weak voluntary efforts was $6 \cdot 0 \pm 0 \cdot 9$ Hz, compared with $7 \cdot 3 \pm 0 \cdot 13$ Hz for intact motor units. Overall, the range of motoneurone firing rates (from minimal to maximal levels of voluntary effort) was significantly affected by the acute deafferentation, but was shifted significantly to lower rates.

* Present address and ‡ permanent address: J. B. Pierce Laboratory, New Haven, CT 06519, USA.

† To whom correspondence should be addressed at: Prince of Wales Medical Research Institute, High Street, Randwick, NSW 2031, Sydney, Australia.

4. During sustained maximal voluntary efforts of at least 30 s duration the firing rate of deafferented motoneurones decreased over the first 5 s but was then maintained, i.e. there was no progressive decline as occurs with normally innervated motor units during fatiguing contractions. This observation supports a reflex origin for the normal decline in motoneurone discharge.

5. It is concluded that muscle afferents in the common peroneal nerve provide a net facilitation to the tibialis anterior motoneurone pool, reflexly increasing the motor output at all levels of voluntary drive by approximately one-third.

INTRODUCTION

Peripheral feedback from a contracting muscle is not essential for the ability to direct simple motor commands to specific intrinsic muscles of the hand (Gandevia & Rothwell, 1987; Gandevia, Macefield, Burke & McKenzie, 1990). Recently it has been demonstrated that subjects can also grade their motor commands to muscles acting on the foot without reliance on proprioceptive signals (Macefield, Gandevia, Bigland-Ritchie, Gorman & Burke, 1991; Gandevia, Macefield, Bigland-Ritchie, Gorman & Burke, 1993). Muscle afferent feedback does, however, provide an important facilitatory influence to human α-motoneurones; partial anaesthetic block of the common peroneal nerve lowers the maximal sustainable firing rates of motor units in tibialis anterior, a result that can be explained by preferential block of γ motor axons and hence reduced facilitation of α-motoneurones via muscle spindle afferents (Hagbarth, Kunesch, Nordin, Schmidt & Wallin, 1986; Bongiovanni & Hagbarth, 1990). Bongiovanni & Hagbarth (1990) postulated that a progressive reduction in spindle support during a sustained voluntary contraction could account for the progressive decline in motor unit firing rates during maximal efforts (Marsden, Meadows & Merton, 1971; Grimby, Hannerz & Hedman, 1981; Bigland-Ritchie, Johansson, Lippold, Smith & Woods, 1983; Bigland-Ritchie, Dawson, Johansson & Lippold, 1986; Bongiovanni & Hagbarth, 1990; Gandevia *et al.* 1990; Bigland-Ritchie, Furbush, Gandevia & Thomas, 1992). There is some direct support for this hypothesis (Macefield, Hagbarth, Gorman, Gandevia & Burke, 1991), but this evidence does not exclude other mechanisms, such as inhibition of motoneurones from an intramuscular source (Bigland-Ritchie *et al.* 1986; Woods, Furbush & Bigland-Ritchie, 1987; Garland, Garner & McComas, 1988; Garland & McComas, 1990; Garland, 1991).

For the intrinsic muscles of the hand, muscle afferents provide significant facilitation of volitionally generated motor output; the highest sustainable firing rates of single motoneurones during maximal efforts are about 40% lower in the complete absence of feedback from the target muscle, but do not decline during prolonged efforts (Gandevia *et al.* 1990). In those experiments homonymous muscle afferent feedback was removed by blocking the ulnar nerve distal to the recording site with local anaesthetic, so that only motor activity could be recorded from the nerve proximal to the block. However, the motor repertoire of the human hand is unique and it is unsafe to generalize from this specific case to other human muscles. We have therefore extended this technique to the common peroneal nerve to see whether the maximal firing rates of motoneurones innervating tibialis anterior are similarly reduced when muscles of the lower limb are paralysed and their

homonymous muscle afferent input is removed. In addition, we have determined the minimal discharge frequency that subjects can voluntarily sustain when deprived of muscle afferent feedback. The results indicate that both the lowest and highest sustainable firing rates are reduced by deafferentation of the target muscle, implying that muscle spindle feedback facilitates motoneurone discharge over the full range of voluntary firing. In addition, we provide further evidence that the normal decline in motor unit discharge during prolonged maximal voluntary contractions is dependent on a reflex influence from the contracting muscle. Preliminary results have been published (Macefield *et al.* 1991).

METHODS

Single-unit recordings were obtained from the common peroneal nerve in eight of the twelve experiments reported in the preceding manuscript (Gandevia *et al.* 1993). The minimal discharge rates of tibialis anterior motor units, with two subjects contributing to both studies were recorded in six further studies. Each of the subjects (age range 25–60 years) provided informed consent to the experimental procedures, which were conducted with ethics committee approval.

Experimental protocol

The methodology has been described in full in the preceding paper. Briefly, the subject reclined in an armchair with the knees flexed to 120–145 deg and the ankles to 90 deg, the feet being fixed in an isometric myograph. After brief maximal voluntary contractions had been recorded on both sides, an insulated tungsten microelectrode was inserted percutaneously into the common peroneal nerve in the popliteal fossa of one leg and directed into a motor fascicle supplying tibialis anterior or occasionally extensor digitorum longus. Intrafascicular electrical stimulation through the microelectrode and the recording of mechanically evoked afferent activity were used to define the target muscle of the motor fascicle. The nerve was then completely blocked by perineural injection of 6–8 ml lignocaine (2% with adrenaline) 5–7 cm distal to the recording site. Conduction across the block was assessed throughout the experiment by monitoring the compound muscle action potential of the dorsiflexor muscles evoked by intraneural stimulation. Once the nerve block was complete, subjects attempted to activate the paralysed dorsiflexor muscles while the microelectrode was manipulated in a search for single motor axons.

The discharge properties of the tibialis anterior motor axons recorded during a distal block were compared with those recorded from intact tibialis anterior motor units. For contractions of 50–100% maximal, this comparison involved data on over 400 motor units reported by Bigland-Ritchie, Furbush, Gandevia & Thomas (1992). For minimal efforts we recorded the discharge of 81 low-threshold tibialis anterior motor units using a standard concentric needle electrode in six subjects. For each motor unit the discharge frequency was based on forty to one hundred consecutive intervals in which the subject tried to maintain the discharge at the lowest regular rate with the aid of auditory feedback.

Data recording and analysis

Neural activity was amplified (2×10^4), filtered (0·3–3·0 kHz), monitored audiovisually and stored on video tape (Vetter-Sony PCM 8-channel recorder). Bilateral dorsiflexor EMG (Ag–AgCl surface electrodes, gain 10^5, bandwidth 3·2 Hz to 3·2 kHz) and torque about both ankles (bandwidth DC–100 Hz) were also recorded. All quantitative analyses were performed off-line. The unitary integrity of recordings from single motor axons was assessed by monitoring the morphology of the triggered and delayed spikes, using a dual time–amplitude window discriminator (Bak Electronics), on a storage oscilloscope with a 2 ms sweep. This allows separation of units with spikes of different amplitude and/or different morphology. Recruitment of a new unit with an identical shape would not be identified, but such misclassification should lead to an overestimation of spike frequencies and variability, and thereby to a conclusion opposite to that reached in the present study. Pulses from the window discriminator were used to construct spike-interval histograms (Cambridge Electronics Design 1401 interface). Interval data were compiled in 4 ms bins and cursors placed at the 'shoulders' of the distribution to eliminate doublets, subharmonics of the fundamental frequency and any false-positive acceptances. The coefficient of variation was computed for all

intervals between the two cursors. The recruitment thresholds of single motor axons during attempted contractions of the paralysed muscles were estimated from the torque generated by a simultaneous matching contraction of the contralateral muscle. The spike trains were displayed with contralateral dorsiflexor torque on a chart recorder (Gould ES2000). Thresholds were then measured as a percentage of the maximal contralateral force. For statistical evaluation of the data paired *t* tests and the non-parametric Kolmogorov–Smirnov and Mann–Whitney tests were used. The limit of statistical significance was set at $P < 0.05$.

To distinguish the behaviour of the motoneurones following distal paralysis from that of normally innervated motoneurones, we refer to the former as 'deafferented' motoneurones. This is not intended to imply that all peripheral inputs affecting the motoneurone pool were removed.

RESULTS

Unit sample and recruitment thresholds

Recordings were made from fifty-four single motor axons in the common peroneal nerve, proximal to a complete anaesthetic block of afferent and efferent conduction. With the exception of two motor axons innervating extensor digitorum longus, all single axons (hereafter referred to as *deafferented motoneurones*) were sampled from motor fascicles supplying tibialis anterior. In the absence of feedback from the target muscle, all subjects could readily increase or decrease the firing rate of a motoneurone and could sustain a fairly constant discharge frequency. The behaviour of one motoneurone recruited with voluntary efforts during complete paralysis is illustrated in Fig. 1. An attempt to estimate the relative recruitment threshold objectively was made by asking the subject to generate a slowly increasing bilateral effort until the motoneurone was recruited. In this example, the contralateral matching force was about 25% of the maximal voluntary force measured at the beginning of the experiment. It should be recognized that this method based on bilateral matching probably underestimates the recruitment threshold of the motoneurone under normal conditions (Gandevia *et al.* 1993). However, it should still allow a valid comparison of the behaviours of different deafferented motoneurones.

Recruitment thresholds were estimated for thirty-three of the fifty-four deafferented motoneurones. The majority were arbitrarily classified as low-threshold motoneurones: ten (30%) were recruited at levels below 1% of the maximal voluntary force, thirteen (39%) had thresholds of 1–5% and eight (24%) of 6–10%. The force thresholds of the remaining two motoneurones were 17 and 25% of maximum, and these were classified as high threshold. Of the motoneurones for which matching contractions were not performed, ten were found during sustained maximal voluntary efforts and four during sustained efforts estimated by the subjects to be approximately half of maximum; the remainder (8 axons) were recorded during lower levels of unilateral effort.

There is marked hysteresis in the relationship between the level of effort (and neurogram) on the paralysed side and the matching force on the contralateral side (Gandevia *et al.* 1993). This is relatively independent of the level of effort and the rate of its production. While this will not affect the distribution of thresholds which we measured it could underestimate their absolute value. If, as is customary, recruitment is assessed by using ascending ramps of effort, we calculate that the values observed here should be increased about 2·5-fold to give the percentage of the maximal voluntary motoneurone output at recruitment.

Discharge behaviour during maximal voluntary efforts

In six experiments on four subjects, thirteen deafferented motoneurones were studied during sustained maximal voluntary efforts of at least 30 s duration. The firing rates of seven motoneurones were followed for the entire 30 s, whereas the
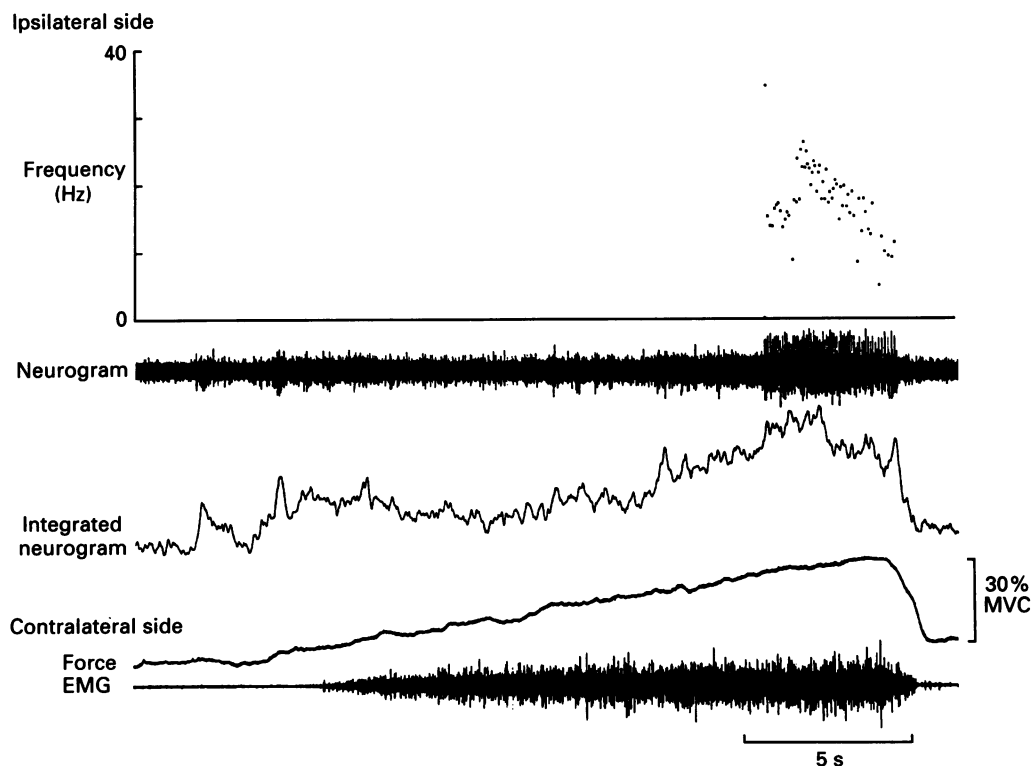

Fig. 1. Recruitment of a motoneurone (extensor digitorum longus) during complete anaesthetic block of the common peroneal nerve distal to the recording site. Discharge frequency, filtered neurogram and integrated neurogram are shown in the upper three traces. The lower two traces show the force and EMG on the contralateral (unparalysed side). The subject made a slowly increasing bilateral effort which resulted in recruitment of the motoneurone late in the effort.

others were sampled at different times during the 30 s effort. Eight of the motoneurones were low threshold (recruitment at $< 10\%$), two were considered high threshold (17 and 25%), and for three recruitment threshold was not determined. Raw data for a single motoneurone during a maximal effort are shown in Fig. 2 and mean firing rates, calculated over 5 s epochs, are illustrated in Fig. 3 for the seven units followed over the entire 30 s. For the full sample of thirteen motoneurones, the mean discharge frequency at the onset of the maximal effort was 20.3 ± 2.3 Hz ($n = 10$). This declined significantly to 17.2 ± 2.1 Hz ($n = 9$, $P = 0.016$) in the second sampling epoch (5–10 s), but showed no significant decline thereafter. Mean firing rates 25–30 s from the start of the maximal effort were 16.5 ± 2.0 Hz ($n = 9$). As described in the preceding paper (Gandevia *et al.* 1993), subjects generally reported difficulty in sustaining their efforts to the paralysed dorsiflexors during

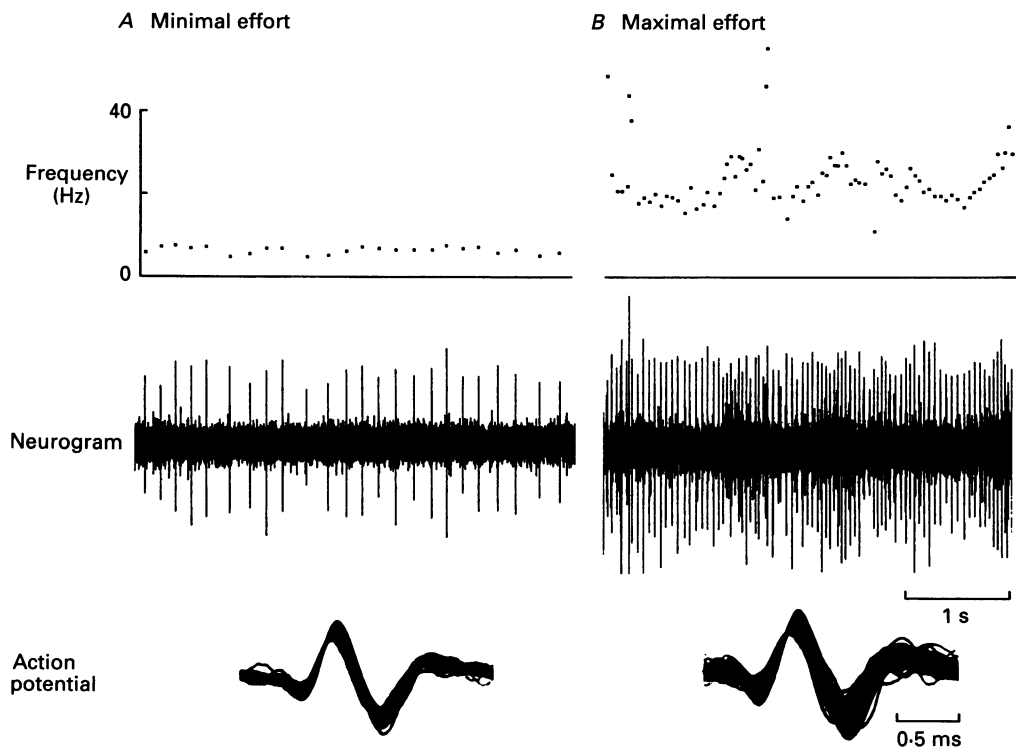*A* Minimal effort   *B* Maximal effort

Fig. 2. Discharge of a motoneurone (tibialis anterior) during complete anaesthetic block of the common peroneal nerve. Discharge frequency and neurogram are shown from typical sequences for a minimal (*A*) and a maximal effort (*B*). The lower panels show superimposed action potentials derived from the motoneurone during the efforts.
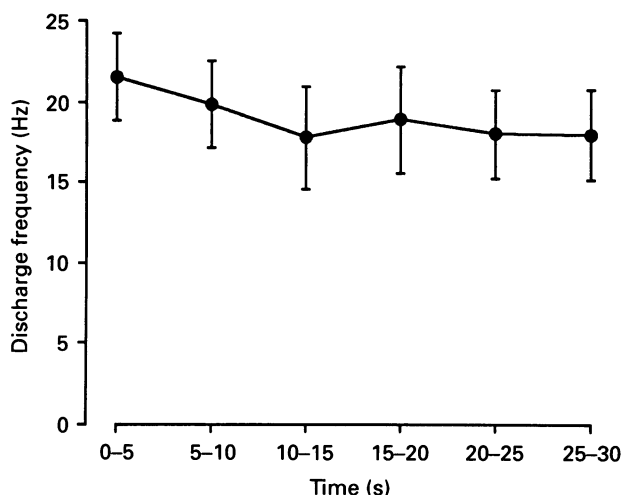

Fig. 3. Mean firing rates of 7 tibialis anterior motoneurones recorded proximal to a complete block of the peroneal nerve during sustained maximal voluntary attempts to contract the paralysed muscle. Each data point is the mean ± S.E.M., computed over intervals of 5 s.

maximal voluntary efforts: averaged multi-unit motor discharge showed a 10% decline in amplitude at the beginning of a sustained effort, but returned to the initial level by the end of the 30 s effort when subjects were encouraged to make a 'super-effort' (Gandevia *et al.* 1993). The early decline in motoneurone firing rates may therefore reflect a decrease in the volitional drive to the motoneurone pool, one which subjects could overcome by increasing their effort.

Maximal and minimal firing rates of deafferented and intact motoneurones

Figure 4*A* shows a pair of cumulative probability histograms of mean firing rates, during maximal voluntary efforts for deafferented and intact motoneurones. Data for the twenty-four deafferented motoneurones (Fig. 4*A*, curve *a*) were obtained from the highest mean frequencies generated by the thirteen motoneurones described above, and a further eleven motoneurones that were isolated for brief intervals at various times during other attempted sustained maximal efforts, using a minimum of twenty-five consecutive discharges. Twelve of the motoneurones were classified as low threshold (recruitment threshold < 10%), and six as high threshold. For six, recruitment thresholds were not determined. Mean firing rates of the low-threshold motoneurones ($21\cdot7\pm2\cdot7$ Hz) were significantly higher than those of the high-threshold motoneurones ($14\cdot0\pm4\cdot4$ Hz, $P = 0\cdot046$, Kolmogorov–Smirnov). Maximal firing rates were $6\cdot4$–$45\cdot4$ Hz for deafferented motoneurones. To determine the effect of deafferentation on maximal firing rates, these data were compared with data compiled from the studies of Bigland–Ritchie *et al.* (1992) on 240 normally innervated single motor units in tibialis anterior during brief maximal voluntary isometric contractions in five subjects. Maximal firing rates for these normally innervated motor units were $9\cdot9$–$61\cdot9$ Hz. The two frequency distributions are significantly different ($P < 0\cdot001$, Kolmogorov–Smirnov); the means of the distributions are respectively $18\cdot6\pm1\cdot9$ Hz and $28\cdot2\pm0\cdot6$ Hz for the deafferented and intact motoneurones, a difference of $9\cdot6$ Hz. It should be noted that the firing rates for normally innervated motor units conform to a normal distribution.

Figure 4*B* provides data for eight deafferented motoneurones and 274 intact motoneurones during brief half-maximal voluntary efforts. Three of the deafferented motoneurones were classified as low threshold; thresholds for the others were not determined. Firing rates for the deafferented motoneurones were $8\cdot2$–$15\cdot5$ Hz (mean $10\cdot8\pm1\cdot1$ Hz). Those for intact tibialis anterior motor units were $9\cdot1$–$27\cdot8$ Hz (mean $16\cdot5\pm0\cdot2$ Hz; Bigland-Ritchie *et al.* 1992). The two frequency distributions are significantly different ($P < 0\cdot001$, Kolmogorov–Smirnov). Again the data for firing rates of normally innervated motor units conformed to a normal distribution.

Data for the minimal firing rates that subjects could sustain without the discharge becoming erratic or interrupted by pauses are presented in Fig. 4*C*. Seven motoneurones were studied during weak efforts, in which subjects could sustain a tonic discharge for at least 5 s. Six motoneurones had low recruitment thresholds. Minimal sustainable firing rates of these deafferented motoneurones were $2\cdot8$–$9\cdot2$ Hz (mean $6\cdot0\pm0\cdot9$ Hz). These rates were slightly but significantly lower than those of 81 intact motoneurones (mean $7\cdot3\pm0\cdot13$ Hz, $P < 0\cdot05$).
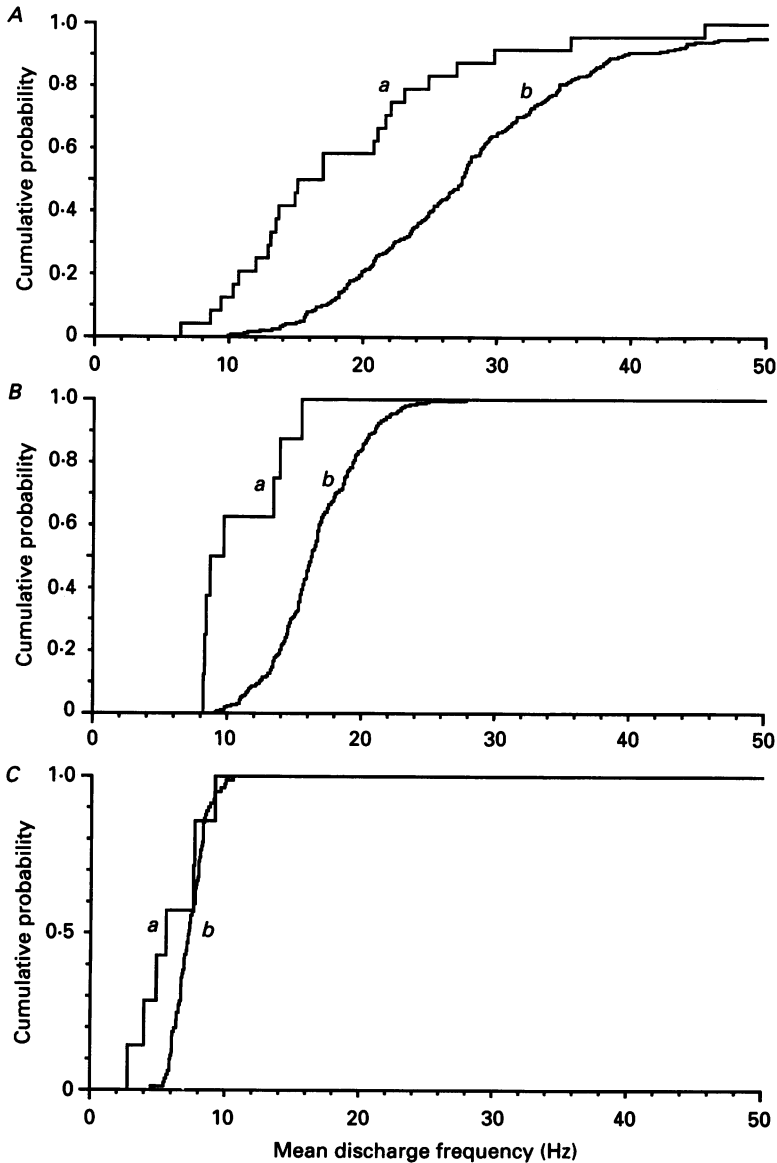
Fig. 4. Firing rate distributions of tibialis anterior motoneurones recorded proximal to a complete block of the peroneal nerve (deafferented motoneurones, curves *a*) and of normally innervated motor units recorded from tibialis anterior (intact motoneurones, curves *b*). Data from the deafferented motoneurones were obtained during maximal voluntary efforts ($n = 24$, *A*), efforts estimated by the subjects to be approximately half this level ($n = 8$, *B*), and during attempts to generate the lowest sustainable firing rates ($n = 7$, *C*). Data from the intact motoneurones were obtained from 240 single motor units during brief maximal voluntary contractions (MVC), from 274 motor units during brief efforts at 50 % MVC (Bigland-Ritchie *et al.* 1992), and from 81 intact single motor units during minimal voluntary contractions (present study).

Various studies have attempted to define the minimal firing rates of human motor units. Comparing the interspike intervals for different tibialis anterior motor units at the onset of a weak voluntary contraction, Petajan (1981) obtained a mean value of 124 ± 26 ms (8 Hz); these motor units could be made to fire up to 11 Hz before a second motor unit was recruited. Hannerz (1974) reports minimal values of 7–12 Hz for this muscle, while Stålberg & Thiele (1973) found lower values for tibialis anterior, with the 'limit frequency' being generally 5–7 Hz. While the difference
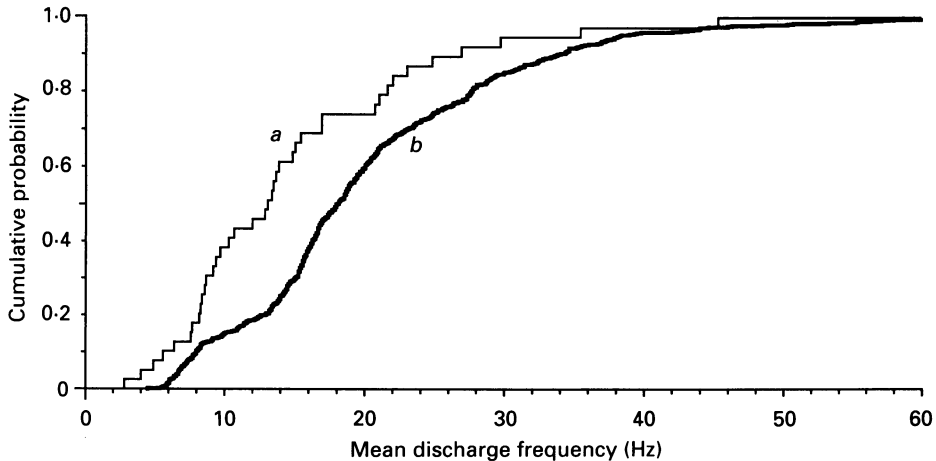

Fig. 5. Distributions of mean discharge frequencies for deafferented ($n = 39$, curve a) and normally innervated ($n = 595$, curve b) tibialis anterior motoneurones across the full range of voluntary drive. The distributions were pooled from the three sets of cumulative probability histograms presented in Fig. 4.

in discharge rate between intact and deafferented motoneurones was small in the present study (1·3 Hz), at low firing rates a small *absolute* difference in frequency represents a larger *relative* difference: for example, the absolute difference between 6 and 7·3 Hz is an increase in discharge rate of 22%.

The data from all histograms in Fig. 4 were pooled to examine the range of motoneurone firing rates during voluntary efforts performed in the absence and presence of muscle afferent feedback (Fig. 5). The mean discharge frequency of the intact motoneurones was $20 \cdot 1 \pm 0 \cdot 4$ and $14 \cdot 7 \pm 1 \cdot 4$ Hz for the deafferented motoneurones. Thus the curve for deafferented motoneurones was displaced to the left of the distribution for the intact motoneurones by 5·4 Hz, with little change in the range. The difference between the two curves represents an estimate of the net facilitation provided to the motoneurone pool by afferents from the target muscle, its synergists and to a small extent from cutaneous afferents across the full range of effort (Gandevia *et al.* 1993).

Firing rate variability of deafferented motoneurones

The regularity of motoneurone firing during sustained efforts was assessed by calculating the coefficient of variation (standard deviation divided by mean discharge frequency) for each motoneurone at each level of voluntary effort. For the seven studied during minimal voluntary efforts, eight during half-maximal efforts, and twenty-four during maximal efforts, the mean variability of discharge at these three levels was $33 \cdot 4 \pm 7 \cdot 8$, $25 \cdot 6 \pm 4 \cdot 3$ and $20 \cdot 5 \pm 1 \cdot 3$% respectively. Although variability

appears to be inversely related to effort, these differences were not statistically significant. Overall, the variability in firing rate for all fifty-four deafferented motoneurones was $23 \cdot 6 \pm 1 \cdot 3 \%$.

<div align="center">DISCUSSION</div>

The present study has shown that at all levels of voluntary drive the mean firing rates of motoneurones innervating tibialis anterior are lower, by approximately one-third, when deprived of afferent feedback from the contracting muscle. The range over which these deafferented motoneurones could fire steadily was slightly lower than for fully innervated motor units in tibialis anterior, $42 \cdot 6$ and $52 \cdot 0$ Hz respectively. However, the upper and lower limits of the firing range were lower following deafferentation, indicating that the voluntary firing range of the motoneurone pool was shifted downwards by the acute deafferentation.

The present observations on a large sample of motoneurones innervating tibialis anterior are similar to but extend the findings for motoneurones innervating intrinsic muscles of the hand (Gandevia *et al.* 1990). The similarities could not have been predicted because the hand has a unique motor repertoire. The similarities in the role of afferent feedback would be consistent with other factors, e.g. descending control, being more critical for the discrete motor capacities of the hand. In a number of areas the present findings extend the earlier study; in that study no attempt was made to determine the minimal firing rates that subjects could sustain voluntarily, maximal firing rates were measured for only seven motoneurones in two subjects and recruitment thresholds were not defined.

Classification of motoneurones

In the present study, an attempt was made to estimate the recruitment thresholds of the motoneurones. Because the target muscle was paralysed, thresholds were estimated indirectly by measuring the contralateral force at which the motoneurone was recruited during a slowly increasing bilateral effort; high-threshold moto-neurones were classified as those that were recruited at levels $> 10 \%$ of the maximal contralateral force. This method of assessing recruitment thresholds with the contralateral force underestimates the actual recruitment threshold. As described in the accompanying paper (Gandevia *et al.* 1993), a marked hysteresis between motor command and contralateral force was evident during ascending and descending ramps of effort: for a given contralateral force, the motor command to the paralysed leg was greater during ascending ramps than during descending ramps. Had the recruitment thresholds been measured during descending ramps, higher absolute thresholds would have been found.

During maximal efforts, the mean firing rates of the deafferented motoneurones classified as high threshold were significantly lower than those classified as low threshold. This fits with some (Freund, Büdingen & Dietz, 1975; Monster & Chan, 1977) but not all observations on normally innervated muscle (Bigland & Lippold, 1954; Hannerz, 1974; Grimby & Hannerz, 1976). There are insufficient data to determine whether the acute deafferentation differentially alters the discharge properties of low- and high-threshold motoneurones. Interestingly, Grimby & Hannerz (1976) observed lower discharge frequencies of the high-threshold motor units in tibialis anterior following a reduction in muscle afferent feedback, induced

by either perineural ischaemia, anaesthesia or cooling of the target muscle. In the present study, removal of muscle afferent inputs by anaesthesia may have reduced the 'excitability' of high-threshold motoneurones preferentially via supraspinal or spinal mechanisms. However, with or without differential partitioning of the reflex effects of muscle afferents onto low- and high-threshold motoneurones, a reduction in net excitation (from all sources) during an attempted maximal effort will produce a lower than expected discharge frequency in the higher threshold motoneurones.

Reflex effects on motor output by muscle afferents

At all levels of voluntary drive the motor output, as measured by the firing of spinal motoneurones, was depressed by the removal of feedback from the contracting muscles (and, to a small extent, from the skin), indicating that such feedback normally provides reflex assistance to the voluntary drive. This may occur at a spinal or supraspinal level (or both). The magnitude of the reduction in discharge rate during the nerve block provides a quantitative indication of the extent to which muscle afferents in the paralysed muscles and to a lesser extent cutaneous afferents can facilitate the tibialis anterior motoneurone pool. The reflex assistance was apparent at minimal levels of effort and this has implications for the mechanism for determining the minimal firing rate of motoneurones, conventionally attributed to the duration of the after-hyperpolarization (Eccles, Eccles & Lundberg, 1958; Kernell, 1965; Calvin, 1974; Gustafsson, 1984). Recent work on human soleus and flexor carpi ulnaris motoneurones has shown that there is no correlation between the duration of the after-hyperpolarization and the lowest sustainable firing rate that can be generated volitionally (Kudina & Alexeeva, 1992). The present study demonstrates that the inputs to the motoneurone pool can also be a determinant of the minimal firing rates of motoneurones.

Firing rate variability

The variability in discharge frequency, measured by calculating the coefficient of variation for each motoneurone at each level of voluntary drive, was lower than that reported for deafferented motoneurones innervating the intrinsic muscles of the hand (mean variability of 41 % during maximal efforts; Gandevia *et al.* 1990). The deafferented motoneurones innervating the dorsiflexor muscles of the foot discharged with a mean variability of only 21 % during maximal efforts. Although the sample was larger in the present study, the disparity in discharge irregularity may reflect a real difference between the two motoneurone pools. Variability of firing rates in intact motor units is higher for more distal limb muscles (Petajan, 1981). In assessing variability of deafferented motoneurones at different levels of voluntary drive in the present study, discharge irregularity tended to decline with increasing effort, although this relationship was not statistically significant. The discharge variability of intact motor units has also been shown to decline at higher firing rates (Stålberg & Thiele, 1973; Petajan, 1981).

Motoneurone discharge during sustained maximal voluntary efforts

During prolonged maximal isometric voluntary contractions, the firing rates of single motor units decline with time (e.g. Marsden *et al.* 1971; Grimby *et al.* 1981; Bigland-Ritchie *et al.* 1983, 1986, 1991; Gandevia *et al.* 1990). The deceleration is

dependent on signals from the contracting muscle (Bigland-Ritchie *et al.* 1986; Woods *et al.* 1987; Garland *et al.* 1988; Gandevia *et al.* 1990; Garland & McComas, 1990; Garland, 1991; Macefield *et al.* 1991). This has been confirmed in the present study. Although the firing rates of the deafferented motoneurones declined during the first few seconds of a maximal voluntary effort, they did not display the progressive slowing shown by normally innervated motor units; the decline could be overcome by increased effort (Gandevia *et al.* 1993). The initial decline in frequency may reflect, in part, the adaptive properties of α-motoneurones to a constant synaptic drive (Kernell & Monster, 1982*a*, *b*), but it is also likely that subjects are unable to maintain a maximal central drive during a sustained effort (see Gandevia *et al.* 1993). For the intrinsic muscles of the hand, there was no decline in the firing rates of deafferented motoneurones, although this was assessed in only one subject (Gandevia *et al.* 1990); the mean discharge frequencies of five deafferented motoneurones monitored over maximal efforts lasting 30 s was 12.3 ± 0.9 Hz. Conversely, the firing rates of this subject's normally innervated motor units in first dorsal interosseous declined significantly ($P = 0.039$, Mann–Whitney U test) from 19.0 ± 2.4 Hz at the onset of a maximal voluntary contraction to 13.8 ± 0.9 Hz at 30 s (reanalysed from Gandevia *et al.* 1990). Thus, by 30 s the firing rates of the intact motoneurones had approached those of the deafferented motoneurones, being only 1.5 Hz higher ($P = 0.097$, Mann–Whitney U test).

Quantitative data of motor unit firing rates as a function of time during maximal voluntary contractions lasting $\geqslant 30$ s have been obtained for only three human muscles: adductor pollicis, quadriceps femoris and first dorsal interosseous. For adductor pollicis, mean firing rates in five subjects declined by 42% from 29.1 ± 1.1 Hz to 16.9 ± 0.5 Hz over 40 s (Fig. 5 in Bigland-Ritchie *et al.* 1983); for quadriceps the mean rates in eight subjects declined by 38% from 25.6 ± 0.5 Hz to 15.8 ± 0.4 Hz over 40 s (Woods *et al.* 1987), and for first dorsal interosseous the mean rates in four subjects declined by 39% from 21.2 ± 1.6 to 13.0 ± 0.5 Hz over 30 s (Gandevia *et al.* 1990). The maximal firing rates for motor units of tibialis anterior (28.2 ± 0.6 Hz, Bigland-Ritchie *et al.* 1992) declined significantly during brief (10 s) contractions by approximately 5–6 Hz.

If motor units in tibialis anterior behave as in the other muscles, the mean firing rate would decline to below 20 Hz by 40 s, that is to a discharge frequency lower than for the deafferented motoneurones. This would be consistent with a net inhibition of the motoneurone pool developing during the sustained maximal contraction (Bigland-Ritchie *et al.* 1986; Woods *et al.* 1987; Garland *et al.* 1988; Garland & McComas, 1990; Garland, 1991). The source of the inhibitory influence is considered to be the group III and IV intramuscular afferents (Bigland-Ritchie *et al.* 1986), which respond to the metabolites accumulated during contraction (Kumazawa & Mizumura, 1977; Kniffki, Mense & Schmidt, 1978; Kaufman, Longhurst, Rybicki, Wallach & Mitchell, 1983; Mense & Stahnke, 1983; Rotto & Kaufman, 1988). The activity of contraction-sensitive group III afferents decreases during fatiguing contractions, suggesting that these afferents cannot mediate the initial decline in motor unit discharge (Hayward, Wesselmann & Rymer, 1991). However, the spontaneous activity of other group III afferents develops late in a fatiguing contraction (Hayward *et al.* 1991).

An alternative hypothesis for the progressive decline in motor unit firing rates during maximal voluntary contractions depends on disfacilitation of the α-motoneurone pool by a progressive withdrawal of spindle-mediated fusimotor support (Hagbarth *et al.* 1986; Bongiovanni & Hagbarth, 1990). The decline in motor unit discharge frequencies is greater at the onset of the contraction and also greater for motor units with higher initial firing rates (Hagbarth *et al.* 1986). This is supported by the recent observation that the decline in muscle spindle discharge is greatest at the onset of the contraction (Macefield *et al.* 1991). However, Garland (1991) has also shown that maximal voluntary force (and EMG) exerted by soleus is still reduced during fatigue when the majority of large diameter muscle afferents have been blocked by nerve compression. It is therefore likely that both progressive disfacilitation and active inhibition of the α-motoneurone pool by intramuscular afferents contribute to the reflex decline in motor unit firing rates during fatigue. As suggested previously (Gandevia *et al.* 1990), spindle-mediated disfacilitation would be primarily responsible for the initial decline in frequency (see Macefield *et al.* 1991), whereas active inhibition by small diameter afferents would contribute later.

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