Pattern of Pulses That Maximize Force Output From Single Human Thenar Motor Units

C. K. THOMAS,1 R. S. JOHANSSON,2 AND B. BIGLAND-RITCHIE3

1The Miami Project to Cure Paralysis, Departments of Neurological Surgery and Physiology and Biophysics, University of Miami School of Medicine, Miami, Florida 33136; 2Department of Physiology, University of Umeå, SE-90187 Umeå, Sweden; and 3Department of Pediatrics, Yale University Medical School, New Haven, Connecticut 06520

Thomas, C. K., R. S. Johansson, and B. Bigland-Ritchie. Pattern of pulses that maximize force output from single human thenar motor units. J. Neurophysiol. 82: 3188-3195, 1999. We assessed the sequence of nerve impulses that maximize force output from individual human thenar motor units. When these motor units were stimulated intraneurally by a variable sequence of seven pulses, the pattern of pulses that elicited maximum force always started with a short (5–15 ms) interpulse interval termed a “doublet.” The twitch force summation caused by this “doublet” elicited, on average, 48 ± 13% (SD) of the maximum tetanic force. The peak amplitude of “doublet” forces was 3.5 times that of the initial twitches, and twitch potentiation appeared to have little influence on twitch force summation elicited by the “doublets.” For some units, the second optimal interpulse interval was also short. Peak forces elicited by the third to sixth interpulse intervals did not change substantially when the last interpulse interval was varied between 5 to 55 ms, so maximum force could not be attributed to any unique interpulse interval. Each successive pulse contributed a smaller force increment. When five to seven pulses were delivered in an optimal sequence, the evoked force was close to that recorded during maximal tetanic stimulation. In contrast, maximal force-time integral was evoked with one short interpulse interval (5–15 ms) then substantially longer interpulse intervals (>100 ms). Maximum force and force-time integrals were therefore elicited by different patterns of stimuli. We conclude that a brief initial interpulse interval (5–15 ms) is required to elicit maximum “doublet” force from human thenar motor units and that near-maximal tetanic forces can be elicited by only five or six additional post-“doublet” pulses if appropriately spaced in time. However, the rate at which these post-“doublet” stimuli must be provided is fairly uncritical. In contrast, maximum post-“doublet” force-time integrals were obtained at intervals corresponding to motoneuronal firing rates of ~7 Hz, rates close to that typically used to recruit motor units and to maintain weak voluntary contractions.

INTRODUCTION

When a human motor unit is recruited in a voluntary contraction it often fires with two closely spaced impulses, termed a “doublet”, followed by longer interpulse intervals that maintain the contraction (Bawa and Calancie 1983; Desmedt and Godaux 1977; Kudina and Alexeeva 1992). Impulse patterns of one or two short interpulse intervals followed by longer intervals maximize the force-time integral from triceps surae motor units of the cat (Burke et al. 1976; Parmiggiani and Stein 1981; Zajac and Young 1980a,b). Likewise, whole mammalian muscles show similar response behaviors when their peripheral nerves are stimulated (Binder-Macleod and Barker 1991; Cooper and Eccles 1930; Stein and Parmiggiani 1981). Thus the pattern by which motoneurons fire when initially recruited strongly influences the force motor units subsequently generate. The first aim of the present study was to determine the sequence of pulses that maximize force from individual human thenar motor units when stimulated intraneurally. These data provide the information needed to effectively stimulate muscle that cannot be driven voluntarily, thereby providing the possibility of restoring limb movement artificially. The second aim of this study was to examine the magnitude of twitch force potentiation that resulted from the delivery of these stimuli. Twitch potentiation following muscle activation is common in human, cat, and rat motor units (Bagust et al. 1974; Burke et al. 1973; Kernell et al. 1975; Nordstrom and Miles 1990; Olson and Swett 1971; Stephens and Usherwood 1977; Thomas et al. 1990; Young and Mayer 1981). Force changes due to potentiation and different patterns of stimulation could then be compared. Some of the present results have been published as an abstract (Bigland-Ritchie et al. 1997).

METHODS

Subjects and experimental setup

Four men and three women with no history of any neurological disorder were chosen as research subjects. Each subject gave their informed consent to participate in the experiments, all of which were approved by the ethics committee of Umeå University, Sweden. The experimental setup shown in Fig. 1A has been described previously (Westling et al. 1990). Briefly, the subject reclined in a dental chair and the subject’s right arm was extended, the hand supinated, and the forearm immobilized in a vacuum cast. The dorsal aspects of the hand and fingers rested in, and were firmly stabilized by, molded modeling clay. The fingers were also constrained by U-shaped clamps anchored in the clay. The extended thumb rested against a two-dimensional force transducer placed against the interphalangeal joint. The thumb position was adjusted until the force transducer registered 0.5 N resting tension in the directions of both abduction and flexion. Thumb flexion and abduction forces were measured simultaneously at right angles by the use of the two-dimensional force transducer.

Single motor axons of the median nerve that innervate thenar motor units were stimulated electrically through a tungsten microelectrode (Vallbo et al. 1979) inserted into the median nerve ~10 cm proximal to the elbow. After an appropriate nerve fascicle was impaled, the
fixed relation to the pulse pressure cycle, which was assessed from an infrared blood pressure pulse detector attached to the subject’s finger (Westling et al. 1990). Thus all stimuli or pulse trains were separated by ~0.8 s intervals, depending on the heart rate.

Protocol

For each motor unit, we determined the pattern of seven pulses which maximized force output, a process we termed an “interval test.” First, two stimuli were delivered to the motor axon at progressively shorter intervals until they were 5 ms apart. Starting with an interpulse interval of 500 ms, this was reduced in steps of 100 ms to 200 ms (4 pulse pairs), then in 20 ms steps from 180 ms to 80 ms (6 pulse pairs), and in 5 ms steps from 75 ms to 5 ms (15 pulse pairs). This sequence, a total of 25 pulse-pairs, is referred to as “run 1” of the interval test. The interpulse interval that elicited the strongest force was termed the first optimal interval and was the first interpulse interval in all subsequent runs. In run 2, the second optimal interpulse interval was determined by delivering a third pulse at progressively shorter intervals in relation to the preceding force-optimized pulse-pair (Fig. 1B). We repeated this process in runs 3–6 until six optimum interpulse intervals were defined. Thus each pulse train in runs 2–6 involved delivery of 3, 4, 5, 6, and 7 pulses, respectively. Before and after the interval test, each unit was stimulated with 5 pulses at 1 Hz to elicit single twitches (Thomas et al. 1990). Single twitches were also recorded within the interval test when the interpulse intervals were longer than those at which any twitch fusion occurred.

After the interval test, the relation between motor unit force and stimulus frequency was recorded by stimulating each unit for 1–2 s at rates from 5 Hz to 100 Hz as described in Thomas et al. (1991a). This provided values of maximum tetanic force and the frequency required to elicit any fraction thereof. The units were then fatigued with 13 pulses at 40 Hz each second for two minutes and force fatigue indices were calculated (final force/initial force) (Burke et al. 1973; Thomas et al. 1991b).

Data collection and analysis

Motor unit EMG and force data were sampled on-line at 3,200 Hz and 400 Hz, respectively, using SC/Zoom software (Department of Physiology, Umeå University, Sweden). Event markers and stimulus pulses were recorded at 0.3 ms accuracy (Westling et al. 1990). Peak force, force-time integral, time to peak force (contraction time, CT), and time for the force to fall from peak to half-peak force (half-relaxation time) were measured from averages of 5 consecutive twitches recorded before and after the interval test, and from 1 to 3 single twitches obtained within the interval test. For each unit, we normalized the values obtained within and after the interval test to the corresponding initial twitch parameters to assess twitch force and force-time integral potentiation and contractile speed changes. We also normalized twitch force values to the maximum tetanic force to determine twitch/tetanus force ratios.

Contractile responses to multiple pulses (n = 2–7) were measured as described above for twitches (peak force, force-time integral from force start to end, and time to peak force, CT; see Fig. 2, inset) except that no measures of half-relaxation time were made. For each response in a run, the peak force and force-time integral of the initial fixed pulse response (e.g., two pulses in run 2) were subtracted from the values obtained for all pulses delivered (e.g., three pulses in run 2) to determine which last interpulse interval evoked the greatest peak force and force-time integral increment.

Statistics

Mean values ± SD are given. “Doublet” data from all 21 units are provided. Analysis of twitch force potentiation during the interval test was based on the 14 units that completed all runs of the interval test.
using repeated measures analysis of variance with run number as the fixed effect (7 levels; prerun and run 1–6). Least squares linear regression was used to assess correlations between different parameters. Statistical significance was set at $P < 0.05$.

**RESULTS**

Twenty-one thenar motor axons were stimulated intraneurally to determine the temporal pattern of seven pulses that maximized motor unit force. The twitch forces of these units, measured before the interval test, ranged from 3.0 to 44.5 mN (mean 16.1 ± 13.0 mN), contraction times ranged from 37.5 to 91.9 ms (57.9 ± 16.1 ms), and half-relaxation times ranged from 32.5 to 130.0 ms (66.5 ± 21.5 ms), all unimodally distributed. Their tetanic forces in response to 50 Hz stimulation ranged from 28 to 193 mN (99.3 ± 50.6 mN), force fatigue indices ranged from 0.33 to 1.14 (0.83 ± 0.25), and twitch/tetanus force ratios ranged from 0.03 to 0.31 (0.18 ± 0.09). These values and their distributions were similar to those found for the larger population of 45 units studied for other purposes (Thomas et al. 1990, 1991a,b; Westling et al. 1990).

The first optimal interpulse interval was determined for all 21 units, but successful recording from some units was subsequently lost. The number of units from which complete sets of measurements could be made declined to 14 units in run 6. When mean values are shown for the entire interval test (runs 1–6), they are based on data from 14 units. However, the behavior of these units was representative of the initial 21 units.

**Force responses to a pair of stimuli**

Figure 2 shows how the twitch forces of a representative unit summed as pairs of stimulus pulses were delivered at progressively closer interpulse intervals. Peak force and force-time integral were greatest when the pulses were 5 ms apart, and were respectively 3.4 and 5.0 times greater than the values for single twitches (Fig. 3, A and B). Peak force was 39% of the maximum tetanic force (Fig. 3C). Two shocks applied 5 ms apart also elicited the most rapid rise in force and the shortest time to peak force (CT, Fig. 3D). EMG potentials produced by each stimulus were strikingly similar at all interpulse intervals $>5$ ms (Fig. 2). With a 5 ms interpulse interval, the two EMG potentials of most units began to fuse, although force continued to rise or was similar to that produced by a 10 ms interval. At interpulse intervals $<5$ ms, tested prior to the formal protocol,
the force was depressed relative to that evoked by a 5 ms or 10 ms interpulse interval (see Burke et al. 1976).

All but one unit generated maximal force when two pulses were delivered either 5 ms or 10 ms apart (15 and 5 units, respectively). The force from only one unit was greatest with an interpulse interval of 15 ms. The force-time integrals also reached maximum values at 5, 10, and 15 ms for 12, 7, and 2 units, respectively. We termed the short interpulse intervals that generated maximum force “doublet’s” because they resembled the closely-spaced muscle potentials that are often recorded at the onset of voluntary contractions that are termed doublet’s (Bawa and Calancie 1983; Desmedt and Godaux 1977; Kudina and Alexeeva 1992).

Both the peak force and force-time integral elicited by a “doublet” varied considerably between units. For all 21 units, the “doublet” forces averaged 3.5 ± 1.6 times the initial twitch force and were 48 ± 13% of maximum tetanic force. The force-time integrals of the “doublets” were 5.6 ± 3.6 times those of the initial twitches. The greatest summation (“doublet” force/twitch force) occurred in units with weak twitch forces, low twitch/tetanic force ratios (Fig. 4, A and C), and small twitch force-time integrals (not shown). Units with small twitch force-time integrals also showed the greatest force-time integral summation (Fig. 4B). No correlation was found between force summation and tetanic force however. The mean time to peak “doublet force” (CT) was 1.4 ± 0.4 times the initial twitch contraction time. The ratio of “doublet” CT to initial twitch CT was greatest for fast units (Fig. 4D). Force summation (“doublet” force/twitch force) was not correlated to twitch CT.

Force generated by pulses that followed the initial “doublet”

Figure 5A shows, for a representative unit, how force summed as an additional pulse was delivered at progressively shorter intervals in run 4. With an interpulse interval of 120 ms, the last pulse added substantially to the force-time integral but did not contribute to the peak force. Peak force only increased when the last interpulse interval was reduced to 70 ms or less. Figure 5B shows, for the same unit, alterations in peak force of the last pulse in runs 1–6. At long intervals, the last pulse in each run evoked only twitches. The force from the last pulse in each run only increased as the twitches began to fuse with the...
preceding fixed pulse response. At intervals shorter than 45 ms, the force contribution from the last pulse was indistinguishable from the fixed pulse response. It was also independent of interpulse interval during runs 3–6. For this unit, the interpulse interval in run 2 had to be reduced to 5 ms to elicit maximum force, as in run 1. However, for other units, peak forces elicited by pulses in runs 2–6 did not change substantially when the last interpulse interval was varied between 5 and 55 ms. Thus in runs 3–6 and sometimes run 2, the peak force elicited could not be attributed to any unique interpulse interval.

Figure 5C shows, for the same motor unit, the effects of interpulse interval on the force-time integral for the whole contraction. For this and other units, the force-time integrals increased as more pulses were added; the increase was roughly proportional to the number of pulses delivered. This was in contrast to the increase in peak force, which was largest in run 1, declined progressively in runs 2–4, and was negligible thereafter (Fig. 5B).

Figure 6A shows the maximal forces elicited from one motor unit in runs 1–6, recorded when interpulse intervals of 5, 15, 25, 30, 35, and 35 ms, respectively, were delivered. These forces are compared with the force evoked by a constant frequency train of stimuli at 50 Hz (- - -). The maximal force increased during runs 1–4. The largest force increment, relative to the twitch, occurred in response to the “doublet” (run 1). The force increment elicited by each additional pulse became progressively smaller until, in runs 5 and 6, no further force increase occurred.

Figure 6B shows the increase in force output as we gradually added interpulse intervals that maximized the peak force output in runs 1–6. Mean unit force increased from 51 ± 12% of maximal tetanic force in run 1 (“doublet” force) to 92 ± 11% in run 6. It is interesting to note that while a “doublet” elicited approximately half-maximal tetanic force, it took four or five additional pulses to elicit a further 41% maximum tetanic force. Nevertheless, when an appropriate pulse pattern was
applied, almost full tetanic force was achieved with only six or seven pulses.

The mean values for the force and force-time integral increment contributed by the last pulse in each run are shown in Fig. 6. C and D, respectively (●). Although the maximum additional force per pulse was greatest for “doublets” and then declined progressively in runs 2–6, the mean increments in force-time integrals per pulse were similar for each additional pulse. Maximal force output in runs 1–6 was obtained with mean interpulse intervals of 9 ± 8, 19 ± 11, 28 ± 11, 33 ± 10, 36 ± 9, and 29 ± 7 ms, respectively (Fig. 6C, ○). Using these interpulse intervals, maximal force-time integral in runs 2–6 occurred when the last interpulse interval was 104 ± 41, 143 ± 36, 145 ± 52, 134 ± 41, and 144 ± 30 ms, respectively (Fig. 6D, ○). The force-time integral in run 1 was greatest when the two pulses were 7 ± 4 ms apart, on average.

Twitch force and force-time integral potentiation

The twitch forces increased significantly during the course of the interpulse interval test (Fig. 7, A and B). On average, twitch forces increased from 17.4 ± 11.5 mN, measured before the test, to 23.9 ± 11.5 mN at the end of run 6. That is, after 675 pulses had been applied over approximately 4 min, twitch force was 1.5 ± 0.6 times initial values. Force-time integral values were 1.7 ± 1.1 times initial values after run 6. In contrast to twitch forces, “doublet” forces did not show any signs of potentiation. At the end of runs 1 and 2, mean “doublet” forces were 46.2 ± 27.1 and 46.1 ± 28.0 mN, respectively. “Doublet” forces were not recorded in runs 3–6 because these runs involved 4–7 pulses.

Figure 7, C and D, shows that twitch force potentiation was significantly greater for units with weak twitch forces and low twitch/tetanic force ratios. Potentiation was not accompanied by significant changes in twitch contraction and half-relaxation times. However, units with long initial twitch CT (slow units) became somewhat faster, whereas those with short initial twitch CT tended to slow down in run 1, with little further change thereafter. After runs 1 and 6, twitch CT was 1.04 ± 0.22 and 1.05 ± 0.23 times initial, respectively. Neither potentiation of twitch force nor of twitch force-time integral was correlated to initial CT or half-relaxation.

DISCUSSION

The pulse sequence that elicited the greatest force from a human thenar motor unit always started with a short 5–15 ms interval between the first two pulses. For all 21 units, this “doublet” caused the force to increase by more than the linear sum of two twitches elicited separately (mean, 3.4× twitch force). Force summation was greatest for weak units with small twitch force-time integrals and with low twitch/tetanic ratios. Some units needed a second short interpulse interval to maximize force. Additional pulses caused a further increase in force, but the extra force elicited became progressively smaller and was less sensitive to changes in interpulse interval. After seven pulses were delivered, the force reached 92 ± 11% maximum unit tetanic force measured by pulse trains at 50 Hz. The pulse pattern that elicited peak force and force-time integral did not coincide after the first short interpulse interval. Longer interpulse intervals maximized the force-time integral whereas shorter intervals maximized peak force.

This behavior of human thenar motor units is similar to that reported previously by Burke et al. (1976), Parmiggiani and Stein (1981), and Zajac and Young (1980a) when single units and/or whole muscles were stimulated in a similar way in cat. Again, all units exerted maximum force-time integral when stimulated by a train of pulses commencing with a 5–10 ms “doublet” followed by longer intervals. Zajac and Young (1980a) measured changes in force-time integrals for isometric contractions of cat medial gastrocnemius motor units. They found that fast units with low twitch/tetanic force ratios often needed two, rather than one, short (transitional) intervals before high force-time integrals could be sustained by subsequent longer intervals, as found here for some human thenar motor units (see Fig. 5). They suggested that two transitional intervals were needed when unit force was less potentiated. The protocol used in the present study did not allow these relationships to be explored in detail. They also found that maximal values required a steady state post-“doublet” interpulse interval of about 1.8× CT for each unit. For human thenar units, the maximum force-time integral during runs 3–6 usually occurred at approximately 140 ms intervals (2.4× mean twitch contraction time). This difference in post-“doublet” interval between the results of Zajac and Young (1980a) and ours probably arises because we selected the interpulse interval that maximized the peak force rather than the force-time integral. Differences may also relate to the lack of fast fatigable type units found in human thenar muscles (Thomas et al. 1991b) and to the absence of any significant correlations between unit force and speed observed in most human motor unit studies (Bigland-Ritchie et al. 1998).

“Doublet” force summation

That the “doublet” force should be substantially greater than the summed force of two twitches elicited separately is explained in part by muscle mechanics. Hill (1949, 1953) demonstrated that, for frog muscle, the muscle series elastic component primarily determines the twitch/tetanus force ratio. If a twitch is preceded by a quick stretch such that the muscle series elastic elements become fully prestretched, the twitch force is then equal to that of the tetanus. Thus the increased amplitude of a “doublet,” compared with a twitch, would result directly from the stretch provided by the contractile response of the first pulse that takes up slack and stretches the unit’s series components. A second pulse following closely thereafter will then elicit a force response substantially greater than that of the sum of two twitches elicited separately. Thus the “doublet” response approaches, to a greater or lesser extent, the force from maximal tetanic stimulation.

In the current experiments, “doublet” forces in run 1 averaged 48 ± 13% maximum tetanic force, and twitch forces averaged 17.8 ± 8.8%. Although “doublet” force-time integrals were 6.8 ± 6.7 times those of single twitches, the increases were mainly because of the increase in force amplitude (3.5 ± 1.6 times initial twitch values). The force-time integral also increased because of the increase in force duration (e.g., CT was 1.4 ± 0.4 times initial). Differences in twitch summation between units, when two pulses were delivered, may depend on differences in series compliance. This predicts that “doublet” force enhancement would be greatest for units with low twitch/tetanus force ratios, as was found here for thenar units. A low twitch/tetanus force ratio would be expected for

...
units that are “on slack,” i.e., at short length in relation to their range of motion. The ten-fold range of twitch/tetanus force ratios reported here, 0.03–0.31, suggests that different units have a correspondingly wide range of functional intrinsic series compliance with the hand in the position adopted in the present experiments.

Differences in resting tension among individual motor units may have contributed to the wide range of twitch/tetanus force ratios, despite the precautions to make all measurements at a standard overall muscle length (see METHODS). The weaker units may thus have been “slacker” than those generating stronger forces. Thomas et al. (1991b) found that thenar units with weaker tetanic forces tended to exert their force preferentially in the direction of flexion.

In addition to stretch of passive series compliance as discussed above, “doublet” force enhancement may also be explained by increased Ca\(^{2+}\) release from the sarcoplasmic reticulum because, in cat muscles, dantrolene sodium abolished part of the short interval force enhancement (Purmiiggiani and Stein 1981). Indeed, twitch force and its time integral are also determined by the duration and amount of actomyosin crossbridge binding (“active state”; Hill 1949), which in turn are related to the amount of calcium released from the sarcoplasmic reticulum per impulse and the time course of its reuptake.

The possibility that the additional force increment came from recruitment of inactive muscle fibers is unlikely because, for intervals of 10 ms or longer, both EMG potentials had similar shapes. For 5 ms intervals, unit EMG potentials began to merge but without force decrements.

**Potentiation**

The potentiation of twitch forces observed during these experiments was similar to that reported previously for human thenar motor units (Thomas et al. 1990), and motor units in other human muscles (Nordstrom and Miles 1990; Stephens and Usherwood 1977; Young and Mayer 1981). Units with weak twitch forces and low twitch/tetanus force ratios potentiated most and were those from which a “doublet” elicited the greatest twitch force summation. Because the sequence in which stimuli were delivered was not randomized, we assume that the influence of potentiation on the magnitude of twitch summation was cumulative. However, it seems unlikely that twitch potentiation played a major role in twitch force summation induced by “doublets.” The twitch forces gradually increased during the entire interval test but not by more than 1.5 times the initial values, whereas the mean “doublet” force was already 3.5 times single twitch forces in run 1. Furthermore, the “doublet” force did not show any signs of potentiation between runs 1 and 2.

**Optimal patterns of stimulation following the “doublets”**

Our results show that an initial “doublet” increased the force three to four times that of the single twitch. After the subsequent five optimal interpulse intervals, the force generated was at near-maximum levels (92 ± 11% maximal tetanic force, Fig. 6B). In contrast, if shocks were applied to thenar human motor units at a constant rate (nonoptimal intervals), it may take up to 20 pulses delivered at 30–100 Hz before maximum tetanic force is reached (Thomas et al. 1991a). Thus when a unit is recruited with a “doublet” it generates force more quickly, primarily by reducing the effect of series compliance (Fig. 6A). Furthermore, that the interpulse periods of the post-“doublet” stimuli required to provide near-maximal force output were rather uncritical (5–55 ms) suggests that the irregular rates at which motor units often fire during voluntary contractions do not necessarily compromise force generation. Irregular motor unit firing rates are common during fatigue, for example, (Griffin et al. 1998) or after spinal cord injury (Thomas and Kozhina 1999).

Numerous studies have noted the occurrence of doublet’s at the onset of human voluntary contractions (Bawa and Calancie 1983; Denslow 1948; Desmedt and Godaux 1977; Kudina and Alexeeva 1992), in animal muscles contracting in response to reflex drive (Cordo and Rymer 1982), during decerebrate cat locomotion (Hoffer et al. 1981; Zajac and Young 1980b), under conditions of both normal and pathological tremor (Elek et al. 1991; Freund 1983), and during spasms of paralyzed muscle (Thomas and Ross 1997). Macefield et al. (1996) assessed the influence of an initial 10 ms “doublet” on the force-frequency relationship for single human toe extensor units when trains of pulses were applied at different constant frequencies (2–100 Hz). They found that such “doublets” effectively elevated the force at low stimulation rates (e.g., 2 to 10 Hz) but caused little force change when delivered during pulse-trains of 20 Hz or above. Thus a “doublet” fired by a motoneuron probably has little effect on force when it occurs during the course of long-lasting, relatively strong contractions. It is most effective at contraction onset when firing rates are low or when the motor unit is engaged in brief actions. Indeed, even at the lowest stimulus rates, the force increment generated by a “doublet” typically disappears within 1–2 s (Macefield et al. 1996).

**General considerations**

The results reported here demonstrate that a brief initial interpulse interval (5–15 ms) is required to elicit maximum “doublet” force from human thenar motor units and that near-maximal tetanic forces can be elicited by only five or six additional post-“doublet” pulses if appropriately spaced in time. Furthermore, the rate at which these post-“doublet” stimuli must be provided to human thenar motor units for near maximal force is fairly uncritical. Hence, if trains of pulses that start with a “doublet” were used in functional electrical stimulation of impaired or paralyzed muscle, rather than the more usual constant frequency trains, this may markedly reduce the risk of fatigue due to transmission failure at the neuromuscular junction and/or within the t-tubular system (Binder-Macleod and Barker 1991; Binder-Macleod et al. 1997). Minimizing the number of pulses would also reduce the overall metabolic load of the neuromuscular system during motor actions.

It is noteworthy that maximum force-time integrals were recorded when most post-“doublet” interpulse intervals were about 140 ms (i.e., runs 3–6), which corresponds to a motoneuronal firing rate of 7 Hz. This rate is close to the minimum rate at which motor units are recruited and it is similar to the rate used to maintain weak voluntary contractions (Monster and Chan 1977; Tanji and Kato 1973a,b). Thus, if preceded by a “doublet,” these low rates would make the human thenar muscles contract with maximum efficiency even when acti-
vated at their minimum rates. Moreover, the similarity between the optimal interpulse patterns described here, in animal studies, and those recorded from muscles or nerves during naturally elicited contractions, suggests that the nervous system indeed uses these advantageous pulse-patterns.

The authors thank G. Westling and L. Bäckström for help during the experiments.

This work was supported by National Institute of Neurological Disorders and Stroke Grants NS-30226 to C. K. Thomas and NS-14756 to B. Bigland-Ritchie, and by Medical Research Council of Sweden Project 08667 to R. S. Johansson.

Address for reprint requests: C. K. Thomas, The Miami Project to Cure Paralysis, University of Miami School of Medicine, P.O. Box 016960 (R48), 1600 NW 10th Ave., R-48, Miami, FL 33101-9844.

Received 18 May 1999; accepted in final form 30 August 1999.

REFERENCES


