Relationship between force and electromyographic activity during rapid isometric contraction in power grip

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Summary Force response and surface electromyographic (EMG) activity of extrinsic extensors and flexors of the hand were measured under 6 target force conditions during rapid pulse isometric contractions (power grip) targeted using an oscilloscope display of exerted and target forces. For target forces ranging from 16.7% to 50% of maximum voluntary contraction (MVC), the rate of force rise increased with the peak force, while the time to peak force remained almost constant. However, at target forces between 66.7% and 101.0% MVC, the rate of force rise leveled off and the time to peak force was prolonged. In association with these changes in force trajectories, modulation of the EMG activity of the flexor digitorum superficialis muscle was observed. At the lowest target force (16.7 MVC), the EMG of this muscle showed a single initial activity: the activity increased linearly up to the 50% MVC target force, while the duration was relatively constant. However, at target forces above 50% MVC, no further increase of the initial activity was observed, while the amplitude and duration of an additional activity progressively increased. These results indicate that the neural control of rapid isometric contraction at target forces at and below 50% MVC differs from that operating at larger target force levels.

Key words: Motor control; Power grip; Rapid isometric contraction; Force; Electromyogram; (Human)

To examine the organization of voluntary movements in a motor control system, many studies have been conducted to identify the invariant characteristic(s) of movement parameters during relatively simple movements involving isometric and anisometric contractions (Freund and Bundinger 1978; Ghez and Vicario 1978; Brown and Cooke 1981; Morasso 1981; Soechting and Lacquinti 1981; Abend et al. 1982; Atkeson and Hollerbach 1985; Flash and Hogan 1985; Ghez and Gordon 1987; Gottlieb et al. 1989; Corcos et al. 1990). Among these parameters, pulse height control (Ghez and Vicario 1978; Ghez 1979; Ghez et al. 1983; Gordon and Ghez 1987a) suggests that the control of an isometric force is attained by varying the rate of force rise to reach a target force while maintaining a relatively constant time to peak force. Several investigators agree that such regulation would simplify the accurate control of force response by reducing the number of variables to be controlled (Ghez 1979; Enoka 1983; Ghez et al. 1983; Gordon and Ghez 1987a).

The concept of pulse height control, however, was evolved from the analysis of tasks with a rather limited set of contingencies, i.e., simple uniarticular planar tasks within a relatively restricted range of force amplitude. Therefore, it remains to be determined whether pulse height control applies to multiarticular tasks over a wide range of force amplitudes. In this study, we chose a power grip task (Napier 1956), which involves many multiarticular muscles to produce force (Long et al. 1970). The pattern of muscular activation results from coactivation of extrinsic and intrinsic hand muscles (Smith 1981), which is different from that in the simple tasks previously investigated.

The purpose of this study was to examine force responses and electromyographic (EMG) activity during rapid isometric contractions (power grip), and to investigate whether pulse height control is observed in the task over a wide force range. It will be shown that pulse height control is observed at and below an intermediate force level, but not above this level.

Materials and methods

The subjects were 4 females (ages 18–19 years) and 2 males (ages 26–31 years), who habitually engaged in
sports requiring skillful movements of the dominant arm. They gave informed consent to participate in these experiments. The subjects sat in a chair with the dominant arm (the right arm in all subjects) abducted 20° and with the elbow flexed 90°. The forearm, which was supported on a horizontal arm rest, was in neutral position. The subject hooked the proximal interphalangeal joints of all 4 fingers around a lever handle. A vertical mechanical stop was aligned with the palmar surface area of the metacarpal bone of the thumb, the carpometacarpal joint of which was abducted 55° radially and 30° anteriorly. The distance between the lever handle and the mechanical stop was adjusted so that the metacarpophalangeal joints of all 4 fingers were flexed almost 40°. The grip force exerted between the 4 digits and the thumb (hereafter, the force response) was measured with a force transducer connected to the lever handle.

The subjects looked at a dual-beam oscilloscope positioned at eye level, 1 m distant. Two beams swept across the screen from left to right in parallel at a speed of 6 cm/sec; one beam indicated the target force, and the other the monitored exerted force. After the beams had passed the center of the screen, the subjects generated a single force pulse with the aim of matching its peak amplitude with that indicated by the target beam. The subjects were instructed to make the force rise as fast as possible to the peak and to then relax their muscles. They were also told that it was unnecessary to start quickly after the beams passed the center of the screen. Instead, they were encouraged to develop the force pulse with precise planning, and were also told not to attempt to correct their response once initiated.

Prior to the experimental session, each subject was requested to slowly increase a grip force up to a maximal voluntary contraction (MVC) for a duration of 2 sec. In the experimental session, 6 different target forces, which were 16.7, 33.3, 50, 66.7, 83.3, and 100% of the MVC force, were used. The experimental trials were organized in 15 blocks, each of which included 6 trials targeted at the 6 different amplitudes (1 trial per target amplitude) presented in random sequence. The inter-trial interval was about 3 sec. Thus, data for 15 trials were collected for each target amplitude in each subject. The inter-block rest interval was 2 min. The subjects were allowed to practice for 5 min before the experimental session.

EMG signals were recorded simultaneously with bipolar surface electrodes placed at the flexor digitorum superficialis (FDS) and extensor digitorum (ED) muscles, and in some subjects at the extensor carpi ulnaris (ECU) and flexor carpi radialis (FCR) muscles as well. The electrodes were placed at the muscle belly with a 2 cm inter-electrode distance. After amplification with an optimal bandpass of 16–1000 Hz, the EMG signals were stored along with force data on a floppy disk after A/D conversion (sampling rate: 1 kHz) with a microcomputer.

In 2 subjects, the EMG signals of the extrinsic hand muscles were more extensively studied using bipolar surface and needle electrodes during the power grip targeted at different forces. Needle EMG signals were recorded with a tungsten semi-microelectrode (3–5 MΩ at 1 kHz). Recordings were obtained at the flexors (FDS, FCR and flexor carpi ulnaris muscles) and the extensors (ED, ECU, extensor carpi radialis brevis and extensor carpi radialis longus muscles).

The peak force and the time from the force onset to peak force were measured. The onset-peak interval is hereafter referred to as the peak force time. The rate of force rise (unit: N/sec) was defined as the quotient of the peak force to the peak force time. The force response and EMG signals for 15 trials in each target condition were averaged by alignment at the force onset. EMGs were full-wave rectified when averaged.

**Results**

**Force responses**

The force responses of 1 subject targeted at 6 different target forces are shown in Fig. 1A (a). All force curves showed a single peaked, bell-shaped pattern, but the force curves of responses targeted at the lower target forces differed from those targeted at the higher target forces. For target forces ranging from 16.7 to 50% MVC (Fig. 1A (c)), the force curves increased in a step-wise manner without change in the peak force time. The trajectories separated immediately after the force onset. However, for target forces ranging from 50 to 100% MVC (Fig. 1A (c)), the force curves showed a common trajectory at the initial phase, and then deviated. The peak force time for the target forces of 16.7, 33.3 and 50% MVC were almost the same (77 ± 4, 79 ± 2 and 79 ± 4 msec, respectively; n = 15 each), whereas those for the 66.7, 83.3 and 100% MVC showed prolongation with increasing target force (95 ± 8, 110 ± 11 and 126 ± 9 msec, respectively; n = 15 each). The rates of force rise for target forces of 16.7–50% also differed from those for target forces of above 50% MVC. As shown in Fig. 1B, the rate of force rise increased in proportion to the peak force in the target force range at and below 50% MVC (closed symbols, r = 0.99, P < 0.001), whereas it leveled off above the 50% MVC target force (open symbols, r = 0.67, P < 0.001).

**EMG activities**

In the 2 subjects in whom the EMG signals of extrinsic hand muscles were recorded simultaneously by surface and needle electrodes, the flexors and ex-
tensors showed extensive coactivation at all target forces. The EMG activities of all the flexors measured by both surface and needle electrodes were similar, as were those of the extensors, at each of the target forces. This finding suggested that EMG signals of the FDS and ED could be used as representative signals for the flexors and extensors in the extrinsic hand muscles, respectively.

Fig. 2 shows the force response and raw EMG records obtained under the 16.7% (A) and 100% (B) MVC target force condition. Under the former condition, the EMG of FDS showed an initial biphasic activity, which started about 30 msec before the force onset and abruptly terminated before the peak. Its duration (approx. 63 msec) was almost the same across all trials.

Under the 100% MVC target force condition, the amplitude of the biphasic wave was increased compared to that under the 16.7% MVC target force condition, while the duration was almost the same. The biphasic wave was immediately followed by a second wave, which was less synchronous with the force onset with higher frequency than that of the initial biphasic wave. It could be argued that the EMG signals of the FDS may be affected by cross-talk from other muscles close to the FDS. This possibility was excluded because the other muscles close to FDS showed similar activity in surface recording. Moreover, the EMG signals of the FDS recorded with the needle electrode also showed a single activity under the 16.7% MVC target force condition, but the duration increased under target conditions above 50% MVC in parallel with that of the surface records.

The EMG signal recorded at the ED under the 16.7% MVC target force condition started at almost the same time as that of the FDS, and persisted even in the declining phase of the force response. This pattern was observed at all target force conditions. The amplitude and duration of the ED EMG under the 100% MVC target force condition were larger than those under the 16.7% MVC target force condition. The results observed for surface recording were also observed for needle recording in both subjects.

Fig. 3 shows the averaged force responses and EMG signals of the FDS and ED muscles under each condition. From 16.7 to 50% MVC target force condition (Fig. 3a–c), the FDS EMG increased with a single
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Fig. 3. Averaged force responses and EMG signals of the FDS and ED under the 6 target force conditions. The EMG signals of the FDS and ED muscles were averaged after full-wave rectification aligning at each force onset. The alphabetical designation of each target force is the same as that in Fig. 1. Note that the ED EMG signal is inverted. The arrows indicate an additional EMG component.

activity, which corresponded to the biphasic wave shown in Fig. 2. At higher target forces (Fig. 3c–f), however, the activity of the biphasic wave remained constant, while the amplitude and duration of the second wave (arrows) increased progressively with peak force. Under the 100% MVC target force condition, the amplitude and duration of the second wave were almost the same as those of the initial wave.

The ED EMGs initiated simultaneously with the FDS EMG and terminated at the declining phase of the force response under all target force conditions. The amplitude and duration of the ED EMG signal increased progressively with peak force, and the signal was more prolonged than that of the FDS EMG. Comparison of the ED EMG signal during power grip with those produced during maximum extension of both the thumb and all fingers revealed that the activation was approximately intermediate between that at rest and that during extension.

Discussion

Pulse height control in power grip

The purpose of this study was to examine the mechanism of control of isometric force production executed over a wide range of force levels during power grip. A major finding for the pattern of the force production was that the rate of force rise at target forces ranging from 16.7 to 50% MVC increased with the peak force while the peak force time was almost unchanged, whereas at conditions above 50% MVC target forces it leveled off while the peak force time increased. Ghez et al. (Ghez 1979; Ghez et al. 1983; Gordon and Ghez 1987a) proposed the operation of a "pulse height control" in the isometric force production at a single joint. In their model, the force production was accomplished by varying the rate of force rise while the time to peak force remained relatively constant. This model was evolved based on the results presented by Freund and Bundinger (1978), and was later partly supported by the findings of Corcos et al. (1990). Our results are consistent with those obtained in this model within a limited range of exerted force, e.g., that at or below the 50% MVC target force. Above that level, however, the concept of pulse height control did not apply because the rate of the force rise leveled off while the peak force time gradually increased.

In previous studies of the control of isometric contractions, the force targets were limited to less than about 50% MVC (Gordon and Ghez 1987a; Corcos et al. 1990), and the tasks involved only a single joint with relatively distinct organization in antagonistic muscles. In the present study, the target force ranged up to and included the MVC and the task involved many joints and many intrinsic and extrinsic hand muscles which are coactivated in force generation (Long et al. 1970; Smith 1981). These differences in methodology preclude any direct comparisons of our results with those of these studies. Therefore, it remains uncertain whether the deviation of the present results from the concept of pulse height control is due to the difference in the force range examined or the task adopted, or both. However, Enoka (1983) reported that in the skilled multijoint movement of double knee-bend weightlifting at various weights lifted, the knee torque shows constant duration in the first, extension, phase but a variation in the subsequent, flexion, phase. The stability of torque duration in the extension phase is consistent with the concept of pulse height control, but its variability in the flexion phase is not. Therefore, it is suggested that pulse height control does not apply to
all movements, including those in the present study, which involved multiarticular joints at large forces up to and including the MVC level.

**EMG activities**

**FDS activity.** In association with the difference between the force trajectories at and below the 50% MVC target force and those above this target force, the FDS EMG demonstrated a complicated pattern of change; only a single initial activity was recruited at target forces up to and including 50% MVC, but this activity remained constant at greater target forces, while amplitude and duration of the second activity increased.

The initial activity was a biphasic wave with a constant duration at the different target forces. We previously observed the same biphasic wave in both rapid isometric and anisometric contractions in elbow extension; the wave has been confirmed not to be a movement artifact (Yamazaki et al. 1993a,b). The biphasic wave of the agonist increased with the movement amplitude in isometric contractions, but its activity leveled off at about 36° amplitudes (Yamazaki et al. 1993a). This pattern is similar to the development of the initial activity of the FDS muscle observed in the present experiments. Brown and Cooke (1984) studied rapid flexion of the elbow joint, and reported that the agonist burst had a single component when the degree of movement was small, but 2 components when it was large. Although their observation has not been supported by other investigators, our results also indicate the presence of 2 EMG components.

The FDS muscle is active during extension of the interphalangeal joints as well as during gripping (Sano et al. 1977; Basmajian and DeLuca 1985). Therefore, the second FDS activity may be due to interphalangeal joint extension after rapid gripping. However, this was not the case, because there was no apparent extension of the interphalangeal joints during the power grip. A rapid and forceful extension of the interphalangeal joints was required to produce EMG activity comparable to the second activity. The possibility that the second FDS activity was derived from cross-talk from other muscles could also be excluded, since it was recorded not only by the surface electrode but also by the needle electrode.

**ED activity.** The ED EMG was coactivated with FDS EMG, but persisted until the force response declined. The magnitude of the ED EMG was intermediate between that during maximum voluntary extension of the thumb and fingers and that at rest. Grip force is greater than hand extension force, probably because the hand must produce a larger force in holding an object but a smaller force in releasing it. Therefore, the hand extensors produce less force than the flexors. Given the intermediate activity of the ED muscle during the power grip and the lesser extension force, it is likely that the ED muscle moderately contributes to the grip force modulation. The moderate contribution of the ED muscle differs from the important role of the antagonist muscle during rapid contractions at a single joint. Ghez and Gordon (1987) studied rapid isometric contractions at the elbow joint and found that the antagonist muscle served to truncate the rising force when very brief peak force times were required. In contrast to the distinct role of the antagonist, the coactivation pattern of the ED and FDS muscles suggests ED muscle assistance in the power grip, such as increasing mechanical impedance to maintain joint stability (Hogan 1984; Solomonow et al. 1988).

**Activities of other muscles.** Many digit and hand muscles are coactivated in the power grip. In the present experiments, EMGs of FDS and ED muscles were recorded. We examined whether the EMG activity of the muscles examined in this study, the FDS and ED, is indicative of that of other flexors and extensors. Some of these muscles may show different patterns of activation, thereby making contributions to force trajectories which differ from those of the FDS or ED muscles when the target forces are graded. However, the surface EMG signals recorded at the other flexors examined in this study showed similar activities over the full range of target forces as the extensors. Moreover, the extrinsic hand muscles provide a major portion of the gripping force, where the FDS muscle contributes in direct proportion to the exerted force (Long et al. 1970). Therefore, we believe that the FDS and ED EMG activities are representative of those of the extrinsic hand muscles in the power grip. The intrinsic hand muscles, such as the interossei, are also active in rotation of the phalangeal joints and flexion of the metacarpophalangeal joints, assisting in the production of the gripping force (Long et al. 1970). In the present experiment, the EMG activities of the intrinsic muscles were not recorded due to experimental restraints. However, we conjecture that the intrinsic muscles may show a pattern of activation similar to that of the extrinsic muscles. The synergistic organization of different muscles with a wide variation in the level of participation for each muscle would demand very complex motor programming, while the synchronization of all the synergistic muscles in the same temporal sequence regardless of their relative contribution to force trajectories would be a much more efficient pattern of organization (Freund and Bundinger 1978).

**Implications of the two phases of contraction**

The magnitude of the initial FDS activity increased with target amplitude, but reached saturation at the target force of about 50% MVC. It is likely that the motor system possesses a limited capacity to activate a
muscle within a short period, such as the initial phase of rapid contractions (Gottlieb et al. 1989). This limitation would become more pronounced when a complex task is performed. Ohtsuki (1981) found that the maximum force exerted by any one of the fingers when the muscles of several fingers were simultaneously activated to produce grip force, was decreased compared to that when the grip force was produced by that finger alone. Furthermore, under this condition the integrated EMG of the finger flexor muscles was also reduced. These findings suggest that the limitation of the maximal EMG activity of individual muscles is exacerbated in association with task complexity. It is likely that the task in the present study revealed the neural constraints limiting the capacity of the motor system to drive the muscles. The second FDS activity may have been necessarily introduced to overcome this limitation. In the context of 2 phases of contraction, the application of a second higher force may function to develop the pulse force generated by the initial agonist EMG volley.

Another explanation for the 2 phases of contraction may relate with strategy employed by the motor control system. It is considered that there are 2 phases in the control of rapid targeted movements. The first is governed by the initial impulse, which drives the limb toward the target, while the second consists of several corrective adjustments. Gordon and Ghez (1987b) suggested that initial errors in force trajectory, which is governed by pulse height control, are corrected within a time `short enough to affect the peak force by internal monitoring of neural commands. This adjustment is apparent as deviations of the peak force time from the regulated value. Such an error correction system would show distinctive operation related to the target level, because a possible increase in force error would be expected by a decrease of the stability of the motor unit firing with increase of the force and/or the rate of force rise (Freund 1983). Sherwood and Schmidt (1980) studied rapid targeted isometric contraction at the elbow joint and found that the variability (S.D.) in peak forces increased up to the intermediate target force level and decreased or stabilized above this level. A similar pattern was found in our study. For example, the S.D. of the peak force values shown in Fig. 1 increased with the target force condition up to an intermediate level; the S.D. was 14.1 N at 16.7% MVC and 30.3 N at 50.0% MVC target. In contrast, the S.D. above that level decreased, and was 22.6 N at 100.0% MVC target, with prolongation of the peak force time. These results suggest that pulse height control is an effective strategy for peak force adjustment targeted below an intermediate force level, but not for that above this target level. Instead, a different control strategy would be utilized, in which the error correction system, as manifested by the second phase of contraction, functions to adjust the peak forces targeted at higher force levels.

In conclusion, in this study of force response and EMG activity during a pulse isometric contraction, force response and EMG activity at and below 50% MVC target force were found to differ from those above this target force, suggesting that the modulations in the 2 force ranges differ. It is proposed that the neural control of the rapid pulse isometric contraction in power grip has 2 stages, the initial one of which is under pulse height control, while the second one, which is introduced at target forces above an intermediate level, is modulated by both pulse height and duration. A primary objective of our future research is the investigation of whether this pattern of control is observed in a wide range of motor tasks, such as that involving a single joint and total body motion.

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