

Research Note

Autogenic and nonautogenic sensorimotor actions in the control of multiarticulate hand movements

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Summary. Human subjects were trained to generate rapid movements of the thumb and index finger and produce a controlled pinch contact force. When unanticipated loads were applied to oppose thumb flexion movements, the desired pinch contact force was achieved by compensatory adjustments of both the thumb and the *index finger flexor* muscles. The nonautogenic finger muscle responses were (1) at latencies of 60 to 90 ms, (2) manifest the first time a load was introduced, and (3) absent for thumb loads introduced during a task not requiring coordination of thumb-finger actions. These intermovement sensorimotor mechanisms may reflect a general task-dependent process contributing to coordination of multiarticulate movements.

Key words: Hand – Load compensation – Motor control – Reflex

The sensory control of multiarticulate movements recently has been examined by analysis of responses to unanticipated perturbations. One fundamental result of these initial studies has been that the compensatory responses are distributed functionally among the constituent muscles and movements. For example, when jaw movement is perturbed during a combined jaw-lip speech action, nonautogenic lip responses are a major component of the compensation (Folkins and Abbs 1975). Such intermovement responses to unanticipated perturbation have been observed in other speech gestures (Abbs and Gracco 1984; Kelso et al. 1982), hand/wrist actions (Traub et al. 1980), and postural adjustments (Cordo and Nashner 1982; Marsden et al. 1981; Nashner et al. 1979). These studies also have indicated that the

response characteristics (e.g., loci, amplitude) depend upon the goal and context of the specific movement as well as the characteristics of the perturbation. These compensations thus appear to be functionally differentiated and not merely generalized responses to a mechanical stimulus. The latencies for these compensatory responses are short; muscle response latencies of 25–80 ms have been reported for speech, 50–60 ms for the hand, and 80–120 ms for the leg. Moreover, these compensations appear to be automatic and are manifest the first time a subject experiences a perturbation.

The present experiment was conducted to determine whether perturbation of the thumb during coordinated movements of the thumb and index finger would yield parallel evidence for short-latency compensatory actions by the index finger. Subjects were three adult human males. The forearm was positioned in intermediate pronosupination and restrained with a cast constructed of orthotic plastic. The cast was formed and padded to restrain thumb movement at all but the distal joint. The index finger was splinted with the distal and proximal interphalangeal joints in relaxed flexion – about 20 and 35°, respectively – leaving the metacarpophalangeal (MP) joint free. Upon combined flexion movements of the thumb interphalangeal (IP) and finger (MP) joints, the pulp of the index finger easily could be brought into contact with that of the thumb. Such contact could be made continuously along the long axis of the pulp of the distal thumb phalanx, depending upon the amount of thumb flexion. A metal band was fitted around the thumb at the level of the nail bed and connected to a brushless DC torque motor via a sector arm and wire. The torque motor was under force feedback control (Abbs and Gracco 1984) and followed thumb movement with a tracking force of 0.3 N. Thumb position was transduced with a rotational transducer attached to the motor shaft.

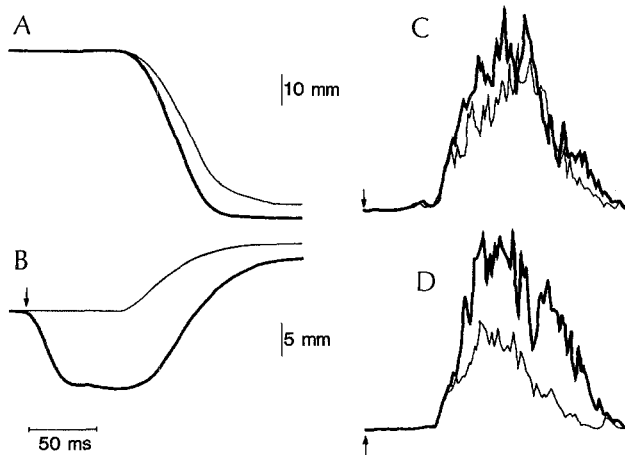


Fig. 1A-D. An example of the load-related changes in the thumb-finger pinch task. Ensemble averages of 17 trials in the load (thick lines) and control (thin lines) conditions for **A** index finger movement, **B** thumb movement, **C** rectified FDS EMG, and **D** rectified FPL EMG. Arrows indicate load onset. Initialization for averaging was movement onset for the finger and thumb movement signals in the control condition. EMG averaging was initialized at the onset of the EMG bursts in the control condition. Load onset served as the line-up point for the thumb movements and all EMG signals in the load condition

Index finger movement at the nail bed was transduced with a two-dimensional strain-gauge transducer (Müller and Abbs 1979). A wafer force transducer was attached to the pulp of the index finger to transduce the thumb-finger contact force. Myoelectric activity from flexor pollicis longus (FPL: sole flexor of the distal thumb phalanx) and flexor digitorum superficialis (FDS: an extrinsic flexor of the finger) was recorded using fine-wire intramuscular or surface electrodes. In all subjects EMG from these two muscles was independent; FDS and FPL could be activated separately.

Subjects were trained (50 to 75 trials) to rapidly flex the thumb and index finger in response to a stimulus tone and produce a briefly maintained peak pinch force of 1.0 N; in effect, subjects precisely tapped the pulps of the thumb and finger together. Each trial was started with the thumb at about 10° flexion and with the pulps of the thumb and index finger separated by approximately 4 cm. The contact force signal was displayed on an oscilloscope and monitored by the subjects. The oscilloscope was triggered by the stimulus tone and subjects were instructed to produce the pinch contact force at approximately the same position of the oscilloscope sweep.

After training, a force that opposed thumb flexion was delivered randomly on 13% of the trials via the torque motor. Subjects were instructed to produce the movements as trained; they were *not*

forewarned regarding the possibility of thumb perturbations. The load magnitude was 1.25 N for one subject and 1.9 N for two subjects. Load rise time was 15 ms and was sustained through the movement task. Loads were timed to begin within a 70 ms interval starting 60 ms prior to FDS activation. Given the variability inherent in voluntary responses to a tone stimulus, the loads could not be timed more precisely; however, loads were distributed throughout the desired interval. The specific response characteristics varied with the timing of the perturbation, as will be described in a later report. The data presented here reflect the more general results of the experiment.

Figure 1 illustrates the load-related changes of finger and thumb movements (A and B, respectively) and FDS and FPL activity (C and D, respectively). The load onset preceded FDS activity onset by 50 to 55 ms for all of these trials, as indicated. Despite the fact that the load reduced thumb flexion (Fig. 1B), all subjects generated average contact forces on loaded trials that were equal to the control trials. The compensation for reduced thumb flexion was accomplished by increased finger displacement (Fig. 1A). Mean increases of 2.5 to 3.0 mm in finger flexion ($p < 0.001$) were observed for all subjects. Increased finger displacement might appear unremarkable inasmuch as the finger might be expected to continue its excursion until thumb contact was made. However, the average velocity of the finger also increased by approximately 10% for loaded trials in all subjects (mean increases of 60 to 85 mm/s, significant at $p < 0.01$ for two subjects). These velocity changes indicated active compensation in the finger movement. As is apparent from Fig. 1A and 1B, thumb loads did not have a mechanical effect on finger movement; as such, the finger movement compensations seemingly were not autogenic.

Myoelectric activity in FDS increased in a manner consistent with changes in finger displacement and velocity. Finger flexor responses with latencies of 60 to 90 ms were seen consistently (Fig. 1C). Only trials where the load preceded the FDS onset by the same interval were included in a given EMG average. To quantify these EMG changes, the areas under full-wave rectified EMG signals were quantified digitally for a 100 ms interval starting with the onset of the FDS agonist burst. In all three subjects the FDS activity was significantly increased from the control by 15 to 20% ($p < 0.05$).

FDS responses in the load condition were not due to crosstalk from FPL and likewise were absent in tasks not requiring thumb-finger coordination. In one control task thumb loads were applied prior to rapid thumb flexion while the index finger was flexed

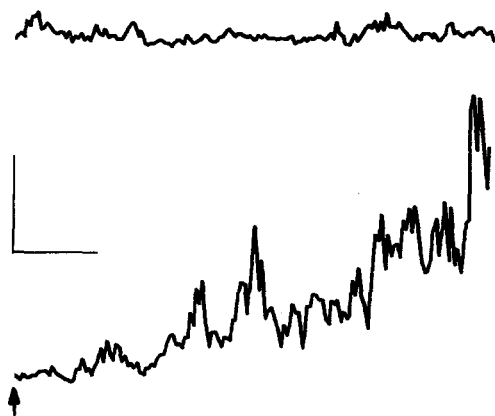


Fig. 2. Ensemble averages of rectified EMG from FDS (top) and FPL (bottom) for 20 trials in which the subject flexed the index finger isometrically against a force transducer with a constant force of 5 N. Perturbations of 2 N (arrow) were delivered to the thumb, just prior to the initiation of thumb flexion. EMG averaging was initialized at load onset. Calibration bars denote 50 μ V and 25 ms

isometrically against a mechanical stop (with a force of 5.0 N to enhance the excitability of the FDS motoneuronal pool). Figure 2 shows averaged FDS and FPL activity for this control task; load onset served as the line-up point for EMG averaging. Averaged FDS activity shows no response, particularly for the latency range in which responses were apparent in the pinch task (60–90 ms); by contrast, long-latency FPL responses are obvious.

We also wished to ascertain that the finger muscle responses were automatic and not conscious responses to the load. Subjects reported being unaware of the finger movement compensations they produced; moreover, compensations were evident for the first load trial. To evaluate further whether the finger compensations might reflect “intended responses,” finger flexion RTs to a thumb load stimulus were obtained. The RT latencies measured from the onset of the thumb stimulus were consistently longer than the FDS response latencies in the pinch task. For example, for S3 the RTs ranged from 87 to 174 ms, with a mean of 112 ms. Only 2 of 62 responses were shorter than 90 ms.

Based upon comparable results from perturbation studies of speech and hand motor tasks, the present data may reflect a mechanism whereby nonautogenic sensorimotor actions assist in coordination of multiple movements in accordance with intended motor goals. As suggested by Bernstein (1967), an important aspect of the control of multiarticulate movements may be the functional linking of the constituent components in order to reduce the control complexity. In general, nonautogenic sen-

sorimotor mechanisms may be particularly suited for achieving coordination among movements. Along these lines, Lacquaniti and Soechting (1982) suggested that the kinematic regularities they observed for elbow and shoulder movements in a reaching task may be attributable, in part, to sensorimotor mechanisms (however, cf. Hollerbach and Flash 1982). While the specific contributions of short-latency sensorimotor processes to control of complex upper limb movements have yet to be determined unequivocally, there is some empirical support from studies of arm postural actions (Cordo and Nashner 1982) and precision grip (Westling and Johansson 1984). The role of afferent mechanisms in multiarticulate arm movements was apparent also in the observations of Polit and Bizzi (1979). That is, in deafferented monkeys, single joint elbow movements were performed without difficulty, while movements involving both elbow and shoulder adjustments were disturbed dramatically.

Nonautogenic responses of intrinsic hand muscles to cutaneous and muscle afferent stimulation have been reported previously for isometric hand tasks (Buller et al. 1980; Caccia et al. 1973). However, the finger muscle compensations observed in the present experiment exhibited a task-dependency unlike more generalized flexor responses, as indicated by their absence in a task not requiring coordinated thumb and finger movements. This disassociation of thumb and finger responses also would appear to extend the observations of Traub et al. (1980) who reported rapid, context-dependent flexion of the thumb and fingers in response to wrist disturbances introduced during thumb tracking tasks. The apparent context-dependency of the finger flexion responses in the present experiment also are similar to those reported for nonautogenic responses in perturbation experiments of speech movements (Abbs and Gracco 1982; Kelso et al. 1982). The task specificity of these orofacial responses, in parallel with observations of “motor equivalence” among the same structures during speech, supports the hypothesis that nonautogenic sensorimotor actions may functionally couple the components of complex motor gestures (cf. Abbs et al. 1984). Similar approaches to the control of limb movements may prove fruitful (cf. Lacquaniti and Soechting 1982).

The present results also indicate that short-latency sensorimotor contributions to digit movement control may be more robust than previously indicated. Rothwell et al. (1982) reported that short-latency, autogenic responses to thumb loads were not fully effective in compensating for unanticipated perturbations. However, as shown in the present experiment, autogenic (thumb) and nonautogenic

(finger) sensorimotor compensations, in combination, were quite effective. Perhaps the potential contribution of sensorimotor actions is underestimated in single joint tasks where only autogenic compensations are permitted. Given the potential significance of nonautogenic sensorimotor actions in multiarticulate movements, the further study of these processes in more natural motor behaviors appears critical.

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