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RESEARCH ARTICLE

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Movement-related potentials with reference to isometric force output in discrete and repetitive tasks

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Abstract This study investigates whether different speed and accuracy constraints in discrete and repetitive index finger isometric force-production tasks influence the characteristics of the movement-related potentials (MRP) preceding and accompanying these tasks. Three components of MRP (*Bereitschaftspotential*, BP, *motor potential*, MP, and *movement-monitoring potential*, MMP) associated with isometric force output were identified and examined. Our principal finding for the MRP amplitude showed that only MMP, not BP and MP, was enhanced at higher rates of force development for both speed and accuracy tasks. That is to say, there was a high correlation between MMP peak amplitude and the rate of force development for both repetitive and discrete force-production tasks. Additionally, the amplitude of MMP was consistently higher for fast, rather than accurate, force outputs. Moreover, the results from analysis of MRP onset times suggest that, in general, the MRP begin earlier for the fast force output than for the accurate force output.

Key words Movement-related potentials · Speed task · Accuracy task · Human

Introduction

Most tasks that people perform with their hands require differentiated movement of the fingers. Fingers play varied roles in creating hand shapes for communicating through gestures, for grasping and manipulating objects of various shapes, and for expressing cognitive-motor acts such as typing or playing a musical instrument (Schieber 1996). In order to understand motor control of hand and individual finger movements, an enormous amount of research has been directed at concomitant neuronal activity (see Georgopoulos 1991; Wing et al. 1996). In particular, activity of single neurons in various brain areas has been shown to be associated with coding force and rate of force change (Evarts 1968; Hepp-Reymond and Maier 1991; Georgopoulos et al. 1992), the direction of intended limb movements (Kalaska and Crammond 1992), limb velocity (Gibson et al. 1985), target position (Alexander and Crutcher 1990), movement trajectory (Hocherman and Wise 1990), the order of sequential movement (Mushiake et al. 1990), and the performance of bimanual tasks (Rouiller 1996).

In a review of the relation between cellular activity in the motor cortex and parameters of force output, Ashe (1997) suggests work in this area is based on a simplistic view that muscles, rather than movements, are represented within the motor cortex. Further, the view that muscles are represented within the motor cortex is at odds with some historical and current conceptualizations. For example, Hughlings Jackson (Jackson 1889; see Georgopoulos 1991, p. 361, for a discussion of this position) suggested "the central nervous system knows nothing of muscles, it only knows movements." Sherrington, as interpreted by Ashe (1997), likewise had a complex view of movement which emphasized the role of the motor cortex as that of integration. Given this more complex understanding, current conceptualizations have moved beyond force itself to questions of direction of movement as well as velocity or rate of force development (see Ashe 1997; Georgopoulos 1991 for reviews.). However, this research has largely been conducted on a single-cell level and thus we are less certain on the level of electrocortical scalp recordings in humans. The present study focuses on rate of force development in humans in a simple force-production task.

Electrocortical scalp activity in humans related to the preparation for hand and finger movements is observed over selective cortical areas depending upon experimental conditions. For example, a slow increase in surface negativity, referred to as *Bereitschaftspotential* (BP; also referred to as *readiness potential*, RP), first described by Kornhuber and Deecke (1965), develops at 1200–500 ms prior to a voluntary, self-initiated motor response. Approximately 60 ms prior to EMG onset, another negative

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potential, referred to as the *motor potential* (MP), appears over the primary project areas of the moving limb, representing activation of the precentral motor cortex (Deecke et al. 1976). There is also a complex positive-negative wave after movement onset which may be associated with precision of movement (Kristeva et al. 1979; Grünewald and Grünewald-Zuberbier 1983a, b). In this paper we will refer to the above measures as *components* of movement-related potentials (MRP; for a review of slow potentials, including MRP, see Birbaumer et al. 1990; Rockstroh et al. 1989).

There are inconsistent findings in the literature regarding the sensitivity of various components of MRP to types of movement patterns in general and to specific kinematic and/or kinetic movement parameters in particular. Numerous studies, using single (*discrete*) movements report significantly larger BP in association with complex tasks compared with simple ones (Schreiber et al. 1983; Kristeva 1984; Benecke et al. 1985; Deecke 1990). *Performance-related* DC shifts are also useful for differentiating simple and complex motor tasks (Lang et al. 1989). More recently, Niemann et al. (1994) reported that a complex motor task (e.g., the movement of matchsticks between the index and small finger) demonstrates a constant high level of movement accompanying negativity throughout the entire trial duration, whereas a simple motor task (e.g., isometric muscle contraction task) reveals an increase in negative d.c. potentials only in close relationship with the onset and termination of the muscle contraction.

Several studies of unilateral movements suggest that a high correlation exists between movement speed and amplitude of the cortical potentials preceding the response (Cooper et al. 1989). Further, Grünewald and Grünewald-Zuberbier (1983a) reported RP amplitudes to be higher before *ballistic* (brief and fast) than before *ramp* movements (slow and smooth). However, no effect of movement velocity on BP amplitude was reported in a similar study by Becker et al. (1976). During a bimanual coordination task, slow negative-going BP displayed larger mean amplitude for the faster required response rate (Wallenstein et al. 1995). Other studies have examined changes in MRP preceding rhythmical movements (Benecke et al. 1985; Lang et al. 1989, 1990) with the finding that MP which precede the initiation of movement have a topographical distribution that depends on the complexity of the upcoming movement patterns. In a recent study, pre-MP and post-MP components of the "steady-state movement-related cortical potentials" associated with repetitive finger movements have been identified (Gerloff et al. 1997). However, this study did not consider the changes in the amplitude of these components under speed and accuracy constraints.

In terms of specific movement parameters, it is generally reported that the amplitude of the BP prior to ballistic isometric presses that require a large force is higher than those that require a lower one (Kutas and Donchin 1974, 1980). Other studies report a positive correlation between the BP amplitude and force level (Wilke and Lansing 1973; Hazemann et al. 1978; Becker and Kristeva 1980). Overall, more forceful self-paced contractions give rise to larger BP (Kristeva et al. 1990). Movement direction (extension versus flexion) does not affect the BP (Deecke et al. Kornhuber, 1980).

Overall, the question concerning how MRP components are sensitive to specific isometric force output patterns, under various speed and accuracy constraints, remains unresolved since few studies are directed at this problem. In order to approach this question, we first examine specific aspects of index finger force-output dynamics. Specifically, we examine whether different speed and accuracy instructions in discrete and repetitive isometric tasks influence the amplitude and onset of various components of MRP preceding and accompanying these tasks. As such, this is the first study to systematically manipulate the isometric force outcome patterns (discrete compared with repetitive), under both speed and accuracy constraints, and examine the effect of these manipulations on MRP preceding and accompanying index finger force-output tasks.

Materials and methods

Subjects

Subjects were all right-handed, according to the Edinburgh inventory (Oldfield 1971), college students (n=12; 6 men, mean age 23 years old, and 6 women, mean age 21 years old) with no history of pathologies of either hand or wrist. Informed consent was obtained prior to the experiment according to the procedures approved by the Compliance Office of the Pennsylvania State University. Subjects received extra class credit for participation.

Experimental tasks

Subjects were seated in an electrically shielded room with the light dimmed for the entire experiment. The subject's arm was placed in a comfortable position on a table with the index finger on a load cell. During the experiment, subjects produced a required task with either the left or right hand by pressing the index finger against the load cell. Feedback of this force output was provided via a computer monitor directly in front of the subject.

The maximum voluntary force (MVF) for a given subject was determined by asking subjects to press the load cell with their right index finger as strongly as possible. The mean values of maximum force production over three trials per subject were computed and defined as MVF. Depending upon the task, one or two target lines were presented on the screen prior to and during the experimental trial. The first was a straight horizontal line indicating 50% of maximum force the subject could produce with the finger. A second line indicated 10% of the maximum force; a third line (pressure line) indicated directly the force with which the subject pressed on the load cell, which was the subject's force trajectory and could be viewed by the subject in real time on the computer screen.

A minimum of 45 trials of four different tasks were performed by each subject. Task 1 required the subject to apply pressure on a load cell as *accurately* as possible until the pressure line on the monitor was equal to the 50% MVF line and to hold it for 5 s. Task 2 consisted of the subject applying pressure as *fast* as possible (without an accuracy requirement) to the load cell to reach the 50% MVF line and to hold it for 5 s. Task 3 required the subject to vary finger pressure on a load cell between the 50% and 10% lines (i.e., to reach the upper and lower target lines) as *accurately* as possible in a 5-s time period. This task produced sine wave-like curves. Task 4 required the subject to vary finger pressure on a load cell producing the sine wave-like curves within the 50% and 10% lines as fast as possible in a 5-s time period. Using these four tasks, both discrete and repetitive isometric force output patterns were examined under conditions of speed and accuracy.

Movement-recording apparatus

Force pressure was measured with Entran Devices EL load cells, which register the displacement via a strain-gauge bridge incorporated in the cell and transduced via a Coulbourn Instrument Transducer Coupler Type A (strain-gauge bridge). The signal was amplified and converted via a Data Translation DT2801-A 12-bit analog-digital (A/D) board with a 200-Hz sampling rate. On-line feedback was provided to the subject on a 640×480 super VGA monitor.

Electroencephalographic recording

A programmable, DC-coupled broad-band SynAmps amplifier (NeuroScan, El Paso, Texas, USA), using an Electro-Cap Electrode helmet, was used to record electroencephalographic (EEG) activity at 9 sites – Fz, F3, F4, Cz, C3, C4, Pz, P3, and P4 – according to the international 10–20 system (Jasper 1958) referred to linked ears. Ag/AgCl electrodes were placed supra- and sub-orbitally to the right eye and 2 cm external to the outer canthus of each eye to record the horizontal and vertical movements in the electro-oculogram (EOG). The EEG signals were amplified (gain 2500, accuracy 0.033/bit) with a recording range set for ±55 mV in the DC to 70 Hz frequency range. The EEG data were digitized at 200 Hz using 16-bit A/D converters. The recording epoch (2000 ms preceding, and 1000 ms following, the peak of finger force output) was triggered by the signal from the load cell when force level crossed the criterion of 5% of MVF. Electrode d.c. shift was compensated for off-line by a 4th-order trend correction of each channel over the entire recording epoch in order to remove a drift in the data that extends beyond the sample epoch (linear detrend option of NeuroScan software). The baseline was derived from the mean of the segment from 2000 to 1800 ms before the trigger point for each channel. Digitized, single-trial EEG and oculographic (EOG) data synchronized with force-production records were processed by the NeuroScan 3.1 software package.

Data reduction and analysis

The characteristics of the force-time impulses were examined separately for discrete and repetitive tasks. The accuracy of finger force output during discrete tasks (i.e., maintenance phase) was estimated by computing the root-mean-square (rms) representing the amount of force error relative to the required force criterion. The first crossing point of the force level rise with the median of the spatial error computed for the final 3 s of the trial duration was used to estimate the time-to-target of the initiated force output. In addition, rate of force development (i.e., peak force of individual trials over time-to-peak force, Pf/Tp; Newell and Carlton 1985) was computed by means of specially written MATLAB M-files to examine the *initial phase* of the force output. The error of this initial rate of force phase was computed based on deviation of peak force level from the required force (e.g., rms).

The level of performance on the repetitive force-production tasks was estimated by computing the rms, SD (standard deviation), and CV (coefficient of variation) of the load cell data with respect to the 50% and 10% of MVF target lines and mean force values both for peaks and troughs. The speed of repetitive finger tasks was estimated by computing the number of peaks and troughs over the entire trial duration and the number of output cycles per second. In addition, the initial phase of the repetitive finger force-production task was estimated by computing the rate of force development in the first cycle as well as the deviation of peak force level from the required force.

EEG continuous data sets were epoched and averaged by the NeuroScan software package. A minimum of 25 sweeps were averaged following artifact correction. In particular, the transmission of vertical EOG (vEOG) into the EEG was estimated by linear regression in areas of maximum vEOG variance. The EEG was then corrected for blinks by subtracting the blinks as measured in the vEOG weighted by the transmission coefficient (NeuroScan 3.1 software option). MRP were derived from nine electrode sites. Three electrode locations (C3, CZ, and C4) were selected and examined as the most indicative for this type of task constraint. Mean EEG activity over 25 trials for each subject under four task conditions was calculated time-locked to the onset of force production and the grand mean for the 12 subjects calculated. The integrated amplitude of the potentials during each of the three time intervals was calculated from the grand mean data (see Fig. 1).

The peak amplitude of MRP was measured for three time intervals: (1) peak negativity measured between 800 and 500 ms prior to force output, referred to as BP; (2) peak negativity measured between 100 ms and 50 ms prior to force output onset, referred to as MP (Kristeva et al. 1990); (3) peak negativity measured during the force output, referred to as movement-monitoring potentials, MMP (Grünewald-Zuberbier and Grünewald 1978; Foit et al. 1983). With this third component, it was consistently observed that premovement negativity persisted or even increased further until the end of the intended finger force production (see Fig. 1). Peak amplitudes were selected by visual inspection of the individual mean waveforms and marked (Gerloff et al. 1997). Latencies were calculated relative to the force onset when it crossed the 5% level of MVF by using a procedure for estimating changes in mean square error (Stagliano et al. 1991). The interval for this calculation was from 2000 to 50 ms prior to the force onset.

A multivariate, 4-factor repeated-measures analysis of variance (ANOVA) using the two instructions (fast and accurate task requirements) in two force-production tasks (discrete and repetitive) by three electrode positions (C3, CZ, and C4) and two force-production sides (right and left index finger) was used.

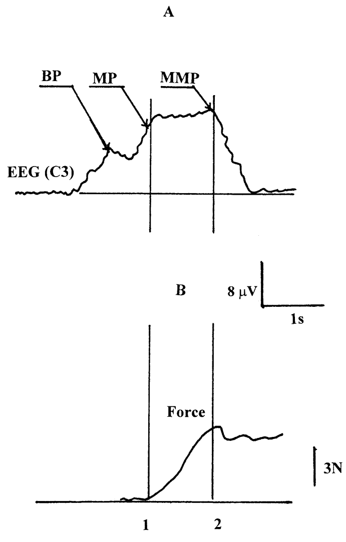

Fig. 1A, B A typical set of data. **A** Three components of movement-related potential (*MRP*) associated with force output and recorded during each of the three time intervals: (1) peak negativity measured between 800 and 500 ms prior to force onset referred to as Bereitshaftspotential, *BP*; (2) peak negativity measured between 100 and 50 ms prior to force onset and referred to as motor potentials, *MP*, (3) peak negativity measured during the force output, referred to as movement-monitoring potentials, *MMP* (**B**). A representative example of the force output, 1-initiation of finger force production, which was triggered by the signal from the load cell when force level crossed the criterion of 5% of maximum voluntary force (MVF); 2-peak force reached

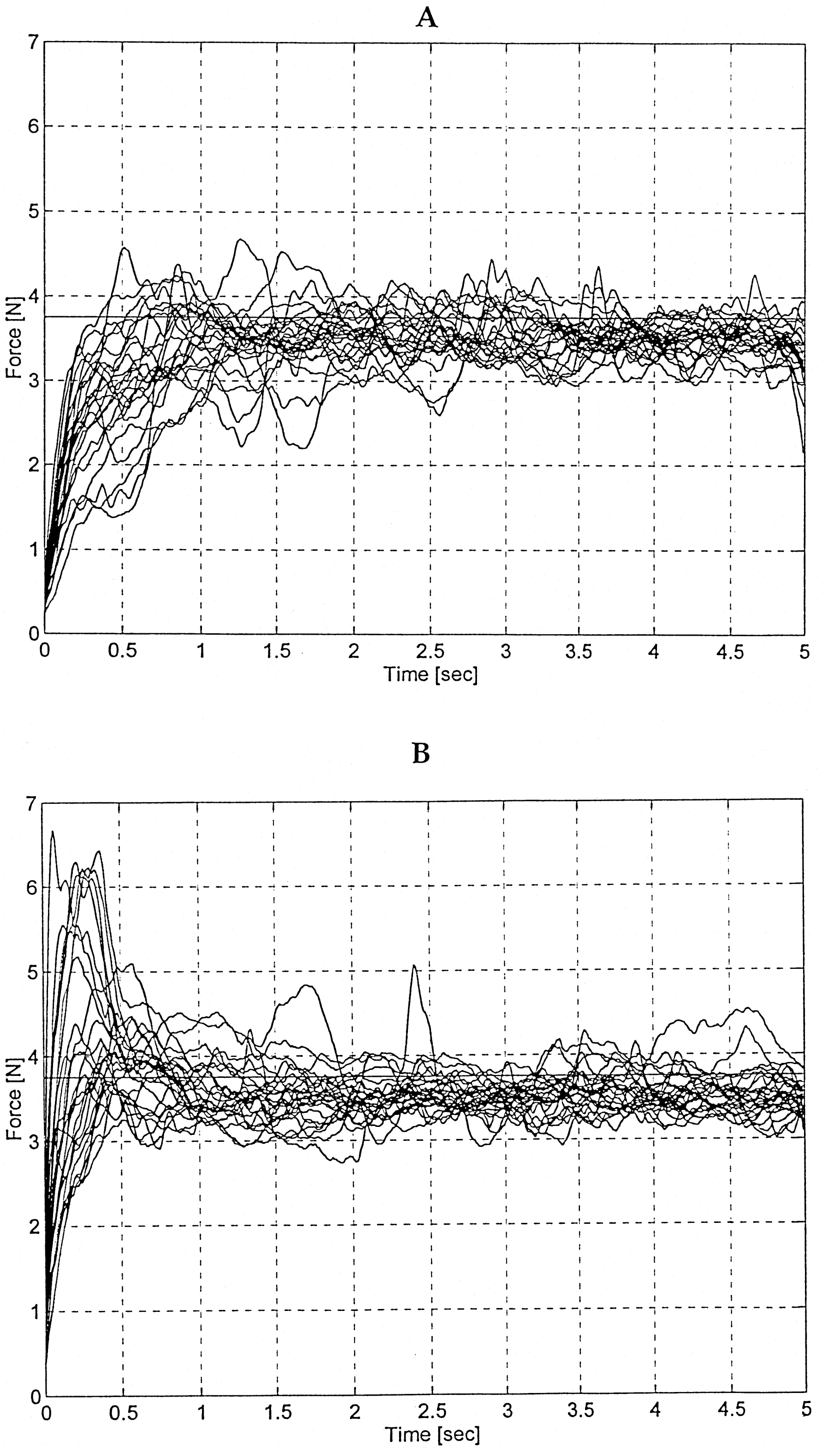

Fig. 2A, B Representative examples of discrete finger force-production task from a single subject. Twenty-five superimposed trials of 5 s duration under: **A** accuracy; and **B** speed instructions

Results

Behavioral data: discrete force-production tasks

Initial phase

Representative examples of subjects' performances on the discrete speed and accuracy finger force-production tasks are shown in Fig. 2. The force-time profiles in this figure suggest that fast responses were usually overshot, whereas accurate responses were slightly undershot for the discrete tasks.

There were significant differences in the force error (e.g., rms) for speed and accuracy instructions, ($F_{1,11}=8.145$, $P<0.01$). The mean peak force was higher for the speed instruction and significantly different from the accuracy instruction ($F_{1,11}=3.485$, $P<0.01$). Accordingly, the rate of force development was significantly

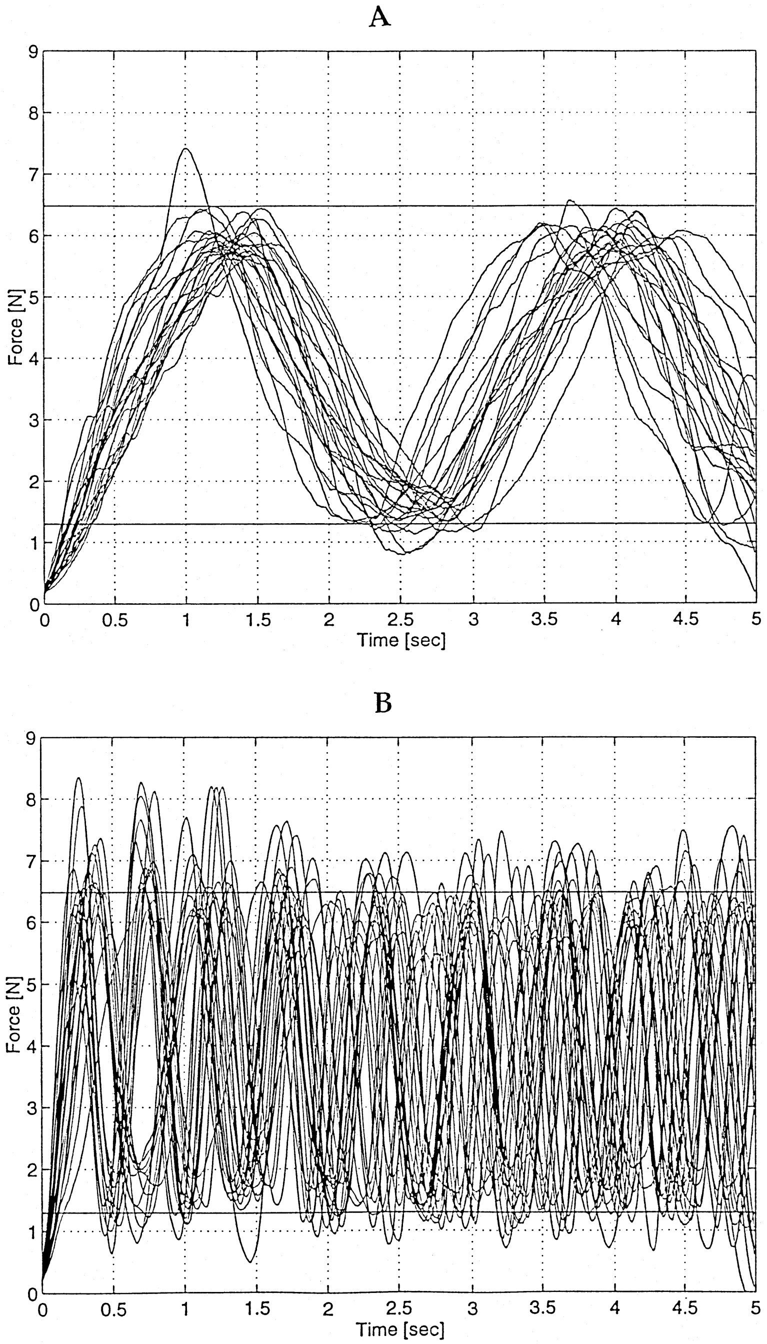

Fig. 3A, B Representative examples of repetitive finger force production task from a single subject; 25 superimposed trials of 5 s duration under: **A** accuracy and **B** speed instructions

higher for the speed instruction ($F_{1,11}$=12.847, $P<0.01$). The main effect of side initiating the force output (e.g., right finger versus left finger force-production within a task) was not significant.

The speed-accuracy instructions induced differences in time to the force target (accuracy, M=1.14 s and speed, M=0.33 s; $F_{1,11}$=56.56, $P<0.001$; M is the mean value). There was also a significant elevation in the value of this variable for the left (M=0.824 s) compared with the right (M=0.645 s) index finger ($F_{1,11}$=5.028, $P<0.05$). Parallel changes for the left and right index fingers resulted in a nonsignificant instruction by force-production side interaction.

Maintenance phase

While there was a tendency for force production to deviate less from the target (rms) under instruction of accuracy (M=0.384) than speed (M=0.471), the effect was not significant. Likewise, while a similar trend appeared for the coefficient of variation of force, this was also not significant. Neither the slight elevation of the coefficient of variation of force for the left versus right index finger nor the apparent instruction by task production side interactions were significant. Thus, according to the ANOVA, instructions for accuracy did not influence force production variability during the final 3 s of the trial.

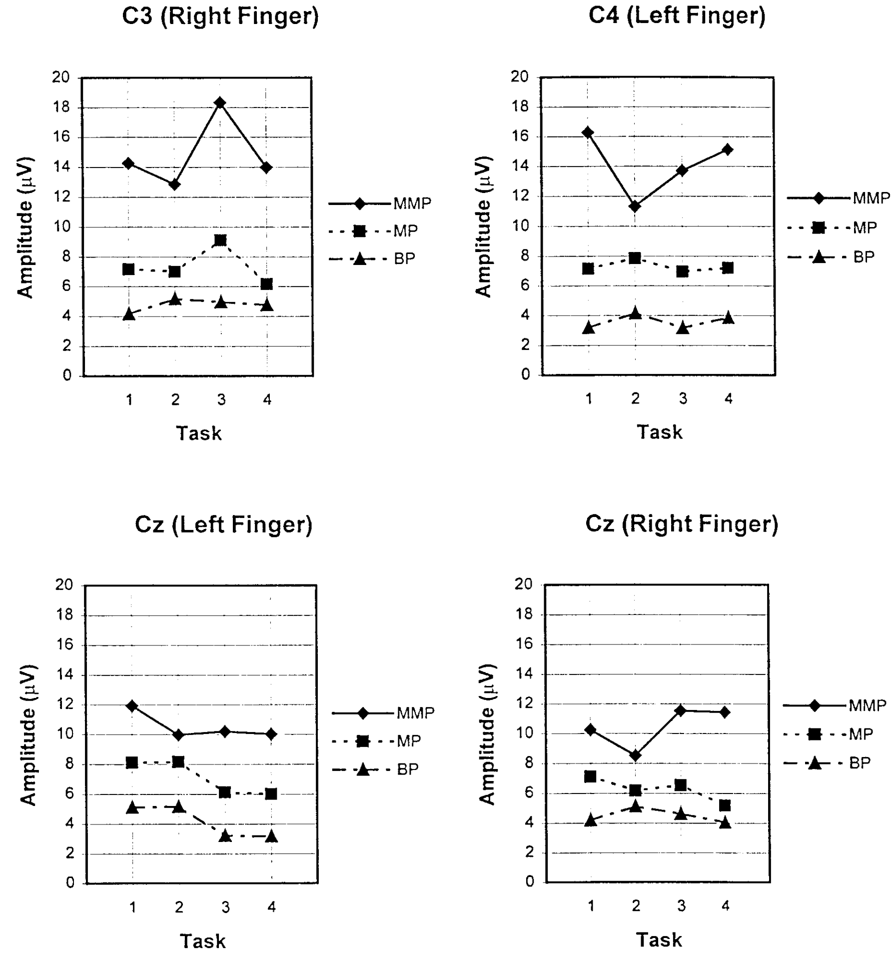

Fig. 4 Experimental data on three MRP components (BP, MP, and MMP) recorded from C3, C4, and CZ electrode positions associated with two (discrete and repetitive) tasks under two instructions (speed and accuracy). *1* Discrete speed task, *2* discrete accuracy task, *3* repetitive speed task, *4* repetitive accuracy task

Behavioral data: repetitive force-production tasks

Initial phase

Representative examples of subjects' performances for repetitive finger force-production under speed and accuracy instructions suggest a pattern that is consistent with the discrete task. As anticipated and depicted in Fig. 3, there were significant differences in the force error of the first cycle (e.g., rms) between speed and accuracy tasks ($F_{1,11}$=5.849, $P<0.01$). The mean peak force for this first cycle was higher for the speed task and significantly different from the accuracy task ($F_{1,11}$=4.182, $P<0.01$). The rate of force development was significantly higher for the speed instruction ($F_{1,11}$=5.298, $P<0.01$). Similar to the discrete task, the main effect of force-production side (e.g., right finger versus left finger force-production within a task) was not significant.

Cycles per second

It was anticipated that the instruction for speed would result in the completion of a greater number of cycles than instruction for accuracy. This was verified, as the instruction effect was highly significant ($F_{1,11}$=48.087, $P<0.001$). There was a dramatic increase in the number of both peaks and troughs from the accuracy instruction (M=3.160) to the speed instruction (M=7.425). Overall, more cycles per second were completed under instructions of speed than accuracy, as shown by an analysis of the number of peaks and troughs.

Root-mean-square

Instructions for accuracy did not influence force-production variability with respect to the force target during the entire trial duration. However, there was a significant instruction effect for a separate 2-way ANOVA applied to the peaks data ($F_{1,11}$=6.858, $P<0.05$). There was a greater variability in matching force to the upper 50% MVF target (on the "upswing" of the cycle, M=0.967) compared with deviations from the lower 10% MVF target (on the "downswing" of the cycle, M=0.578).

Movement-related potentials

Experimental data on three MRP components (BP, MP, and MMP) associated with two (discrete and repetitive) force-production tasks performed under two instructions (speed and accuracy) are presented in Fig. 4. As can be seen, the amplitude of MMP changes as a function of the force-production task and instruction at C3 (for right index finger) and C4 (for left index finger). However, there were no obvious differences in the amplitude of BP and MP (+/–2 μv) between these four tasks. No significant differences in the amplitude of BP, MP, and MMP (+/–2 μv) between the tasks were observed at CZ. Since there were no differences in BP and MP, separate analyses of MMP were conducted for discrete and repetitive tasks.

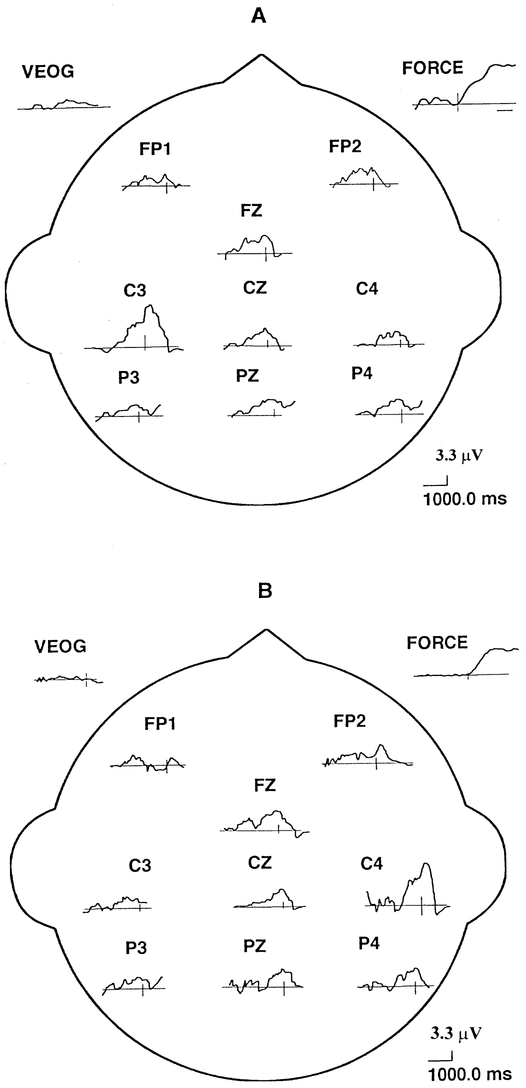

Fig. 5 Examples of scalp-recorded movement-related potentials related to the execution of **A** right and **B** left finger force-production tasks under accuracy condition (based on 25 trials). NeuroScan software package was used for the data collection and analysis

Discrete finger force-production tasks

Figure 5 shows grand mean MRP waveforms at nine electrode positions preceding self-paced right and left index finger force output for discrete force-production tasks. First, there was contralateral preponderance of the MRP, a finding that was previously observed (Kutas and Donchin 1974, 1980; Praamstra et al. 1995, 1996) using the BP as the dependent variable, with the highest amplitude being observed over the contralateral sensorimotor cortex at C3 (for right finger) and C4 (for left finger) regardless of the task requirements.

The mean peak amplitude of the MMP over all 12 subjects was found to increase significantly when subjects were instructed to produce the task as fast as possible ($F_{1,11}=3.773$, $P<0.05$). There was also a significant main effect for electrode position with MMP amplitude ($F_{2,11}=5.347$, $P<0.01$). Further, there was a significant interaction of electrode position and instructions ($F_{2,22}=4.177$, $P<0.05$). However, no significant differences in amplitudes of the MMP were observed between speed and accuracy tasks at the CZ electrode position. Moreover, no statistical differences between speed and accuracy tasks were observed using either BP or MP.

The onset times for the MRP as a function of instruction (speed compared with accuracy) and electrode position for discrete right and left finger force output were analyzed. The maximum onset times for the MRP were estimated in the time interval of –2000+/–50 ms prior to the initiation of force output at the CZ electrode location for both speed and accuracy tasks regardless of the force-production side. There were slightly larger, although nonsignificant, onset times for speed than for accuracy instructions at the CZ electrode position. However, there was a significant effect for instruction with the overall tendency being that there were earlier MRP onset times for speed instruction at the electrode position contralateral to the side of the force output initiation ($F_{1,11}=6.978$, $P<0.05$). A *t*-test of simple effects revealed no significant differences in the MRP onset times between right and left hands within the speed and accuracy instructions.

Repetitive finger force-production tasks

The mean peak amplitudes of the MMP over all 12 subjects for the repetitive right and left finger force-production tasks at three electrode positions were found to be similar to those of the discrete tasks. The peak amplitude of the MMP was found to increase significantly when subjects were instructed to reach the target force as fast as possible ($F_{1,11}=3.773$, $P<0.05$). There was a significant main effect of electrode position on the amplitude of the MMP ($F_{2,11}=6.145$, $P<0.05$). There was also a significant interaction of electrode position with the side initiating the force output and instruction ($F_{2,22}=4.177$, $P<0.05$). Again, no significant differences in amplitudes for the MMP were observed between speed and accuracy instructions at the CZ electrode position. Moreover, similar to discrete tasks, no statistical differences were found for speed and accuracy tasks using BP and MP.

The onset time was analyzed for the MRP as a function of instruction (speed compared with accuracy) for repetitive right and left finger tasks. Similar to discrete tasks, the onset time for the MRP was earlier at CZ for both

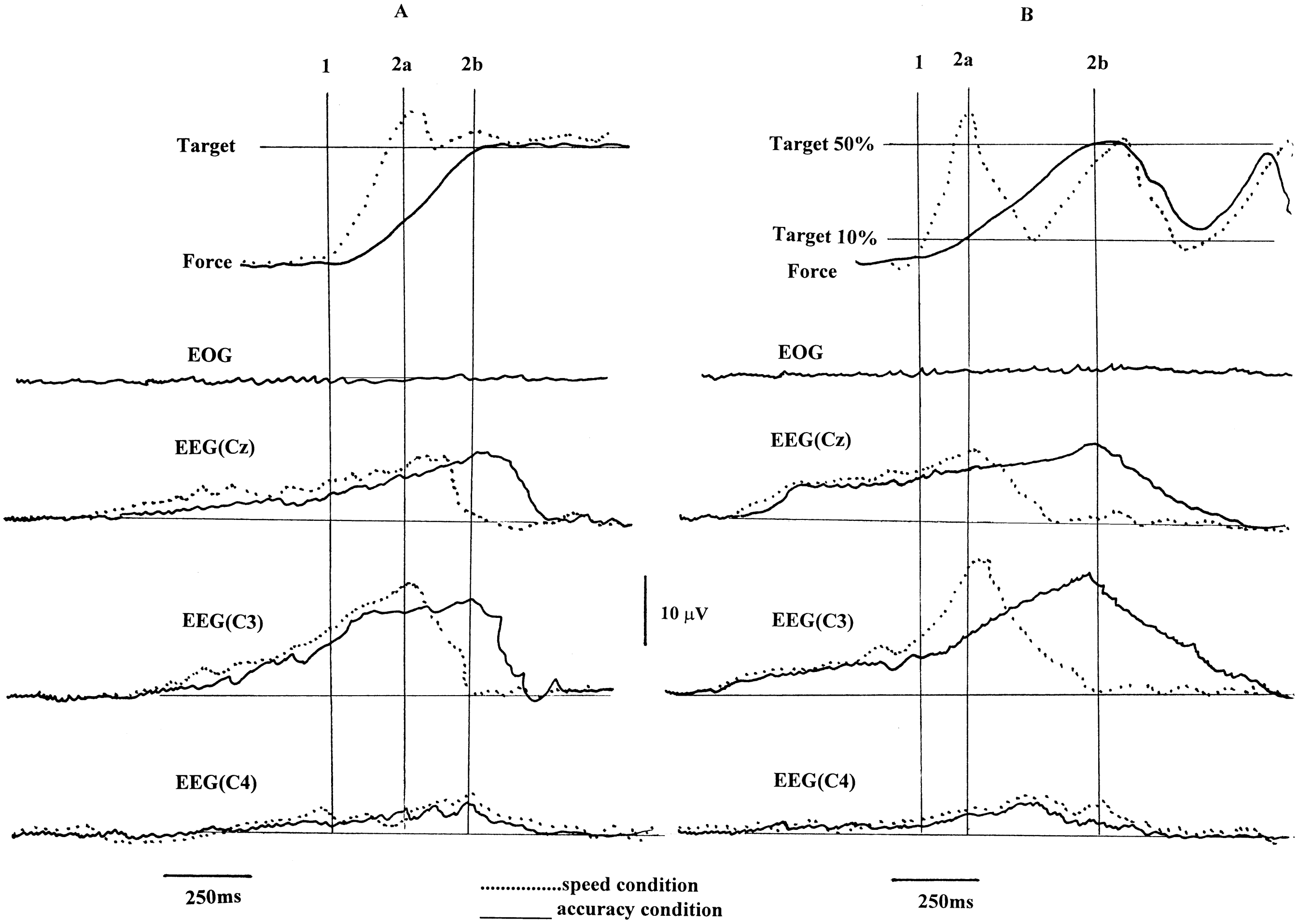

Fig. 6 Examples of force production (right) finger task, vertical electro-oculogram (EOG) and movement-related potentials from C3, C4, and CZ electrode locations (based on 25 trials) in speed and accuracy conditions during **A** discrete and **B** repetitive tasks. *Vertical lines* represent: *1* initiation of force output, triggered by the signal from the load cell; *2a* peak force reached at speed condition; *2b* peak force reached at accuracy condition. MPP components are identified with respect to these lines

speed and accuracy instructions regardless of force-production side. No significant differences were observed for onset time for speed versus accuracy instructions at CZ. There was a significant effect for the instruction with the overall tendency towards earlier MRP onset times for the speed instruction at the electrode position contralateral to the side of the initiating finger force output ($F_{1,11}=3.133$, $P<0.05$). In contrast to the discrete task, a t-test of simple effects revealed significant differences in the MRP onset times between right and left hands within both the speed and accuracy instructions, ($P<0.05$).

Overall course of the movement-related potential

A schematic representation of grand mean MRP waveforms combined with force-production data under both speed and accuracy instructions during discrete and repetitive tasks is shown in Fig. 6. The waveform of the MRPs consistently changed as a function of task, with the tendency to maintain or even to increase throughout the trial duration until the maximum force was attained. This was followed by a positive deflection towards the baseline level when the peak force was reached. This finding is in agreement with Grünewald and Grünewald-Zuberbier (1983a, b), who observed that pre-movement negativity prior to finger positioning movements continued until the maximum displacement had been reached.

There was a significant effect for task with the overall tendency towards larger peak amplitudes of MMP ($F_{1,11}=2.123$, $P<0.05$), and earlier onset times of MRP for repetitive task at the electrode positions contralateral to the side of the initiating finger ($F_{1,11}=6.978$, $P<0.05$). There was also a significant main effect of instruction towards larger peak amplitudes of MMP ($F_{1,11}=4.475$, $P<0.05$), and earlier onset times for the speed task at the electrode positions contralateral to the side of the initiating finger ($F_{1,11}=6.998$, $P<0.05$). The main effect for force-production side was not significant. However, there was a significant 3-way interaction of task (discrete compared with repetitive), instruction (speed compared with accuracy), and position (C3, CZ, and C4; $F_{2,22}=3.374$, $P<0.05$), considering the amplitude of

Table 1 Mean peak amplitude (and SD) of movement-monitoring potentials across scalp locations for each task performed by each subject's right and left finger

Task	F3	Fz	F4	C3	Cz	C4	P3	Pz	P4
Discrete speed									
Right finger	6.25	9.17	3.71	14.25[a]	10.25	3.85	6.15	6.17	4.85
	(2.7)	(4.3)	(2.3)	(5.2)	(4.6)	1.9)	(2.3)	(3.1)	(1.4)
Left finger	1.25	8.25	4.17	4.31	11.91	16.28[a]	4.12	8.17	6.17
	(0.9)	(3.5)	(2.7)	(3.2)	(3.9)	(5.3)	(2.6)	(5.4)	(2.1)
Discrete accuracy									
Right finger	5.28	6.17	3.97	12.85[a]	8.53	3.57	4.17	5.14	4.71
	(3.2)	(2.8)	(2.3)	(4.3)	(3.9)	(1.9)	(2.4)	(2.7)	(2.1)
Left finger	2.15	8.17	4.87	3.12	9.66	11.32[a]	3.18	6.12	6.75
	(0.8)	(3.4)	(3.1)	(2.7)	(3.7)	(3.9)	(1.7)	(2.8)	(3.2)
Repetitive speed									
Right finger	3.28	7.18	2.17	18.32[a]	11.52	5.17	2.65	4.14	5.89
	(2.1)	(3.2)	(0.8)	(5.8)	(3.4)	(2.6)	(1.1)	2.1)	(2.7)
Left finger	1.19	8.17	5.28	4.17	10.19	13.71[a]	4.17	6.18	4.98
	(0.7)	(3.4)	(2.1)	(2.2)	(4.3)	(4.8)	(2.1)	(3.2)	(2.5)
Repetitive accuracy									
Right finger	2.22	8.18	4.32	13.97[a]	11.43	6.76	7.14	5.85	5.17
	(1.3)	(3.2)	(2.3)	(4.3)	(3.3)	(2.1)	(3.2)	(3.2)	(2.6)
Left finger	1.88	6.15	3.76	4.88	10.01	15.12[a]	5.14	5.18	5.11
	(0.9)	(2.3)	(2.1)	(2.1)	(3.2)	(4.9)	(2.6)	(3.2)	(3.2)

[a] The largest value for each task

MMP as the dependent variable. No significant differences in peak amplitudes of the MMP and onset times were observed between different task conditions at the CZ electrode position. Also, a *t*-test of simple effects revealed no significant differences in peak amplitudes of the MMP between right and left hands within discrete and repetitive tasks and within speed and accuracy instructions. Main effects of both task and instruction on amplitude of BP and MP were not significant. Topographic differences of MMP peak amplitude derived from nine electrode positions for each task performed by subjects' right and left index finger are shown in Table 1.

Overall course of data analyses

The relations of peak MMP obtained contralaterally for the hand executing the isometric force output to (1) rate of force development (Pf/Tp), (2) peak force production, and (3) time-to-peak force during discrete task for accuracy and speed instructions are shown in Fig. 7. The linear regression lines are shown for data under both speed and accuracy instructions. As depicted in Fig. 7, for both speed and accuracy instructions the rate of force development strongly predicted the peak amplitude of the MMP. The highest coefficient of correlation (r=0.887, $P<0.01$) was obtained between the rate of force development and the MMP amplitude obtained from the contralateral sites (e.g., C3 for right finger and C4 for left finger) for the accuracy instruction. No correlations were obtained between the rate of force development and the amplitude of both BP and MP at contralateral sites for both speed and accuracy instructions.

Less strong but still significant negative correlations were obtained between the MMP peak amplitude and time-to-peak (r=0.595, $P<0.05$) for the accuracy instruction. No significant correlations were obtained between the MMP peak amplitude and (1) peak force for both tasks, (2) force error for initial phase, r=0.390, and (3) time-to-peak force for speed instruction, r=–0.330. In addition, no significant correlations were obtained between MMP amplitudes and rms force maintenance phase (i.e., the last 3 s of trial duration) for both speed (r=0.362) and accuracy (r=0.365) instructions. No significant correlations were obtained between MMP peak amplitude and onset times and the above-described behavioral variables for the CZ electrode position.

The relations of peak MMP obtained contralaterally for the hand executing the force output to (1) rate of force development (Pf/Tp), (2) peak force production, and (3) time-to-peak force during repetitive tasks under accuracy and speed instructions are shown in Fig. 8. Similar to the discrete task, the highest coefficients of correlation were obtained between peak amplitudes of MMP at C3 and C4 electrode positions and rate of force development during the first cycle of the repetitive task for both speed (r=0.901, $P<0.01$) and accuracy (r=0.907, $P<0.01$) instructions. Neither time-to-peak force nor peaks and troughs of forces, nor their variability during the entire trial duration, were significantly correlated with MMP amplitudes and onset times. No significant correlations were also obtained between MMP peak amplitudes and onset times and the above-described behavioral variables for the CZ electrode position. Again, no correlations were obtained between the rate of force development and the amplitude of both BP

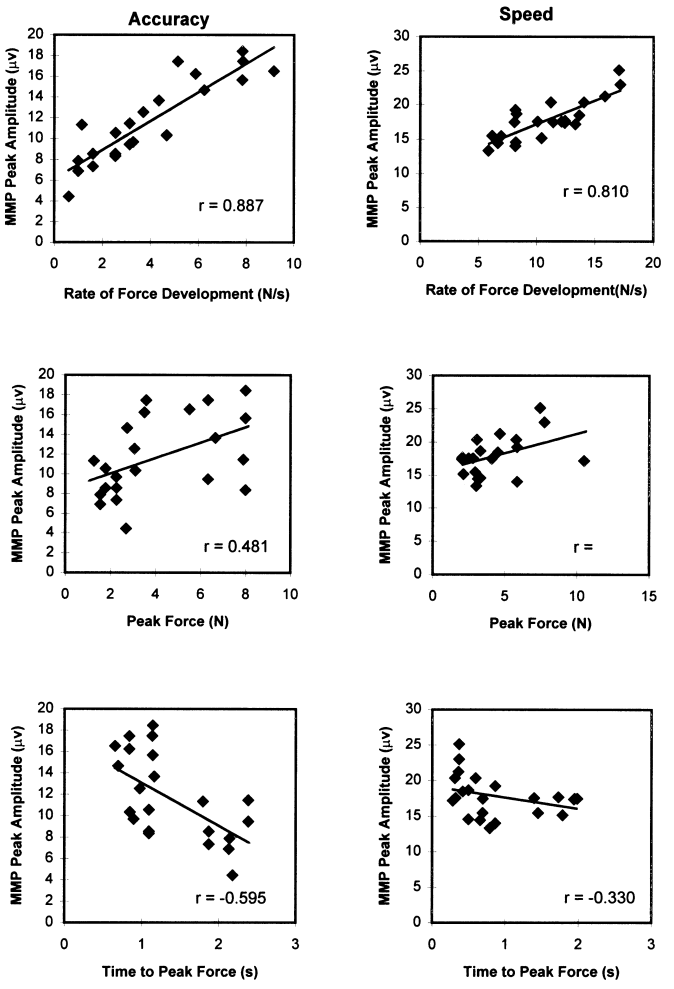

Fig. 7 Relationship of the movement-monitoring potential (MMP) amplitude (mean based upon 25 trials) to rate of force development (Pf/Tp), peak force and time-to-peak force (all data averaged for 25 superimposed trials) for accuracy and speed conditions during discrete task. Pearson pair-wise correlation coefficients (*r*) that are listed in legends of each plot are obtained based upon aggregated data for all 12 subjects and both right and left fingers. Best-fitting linear regression lines are superimposed on the scatter plots

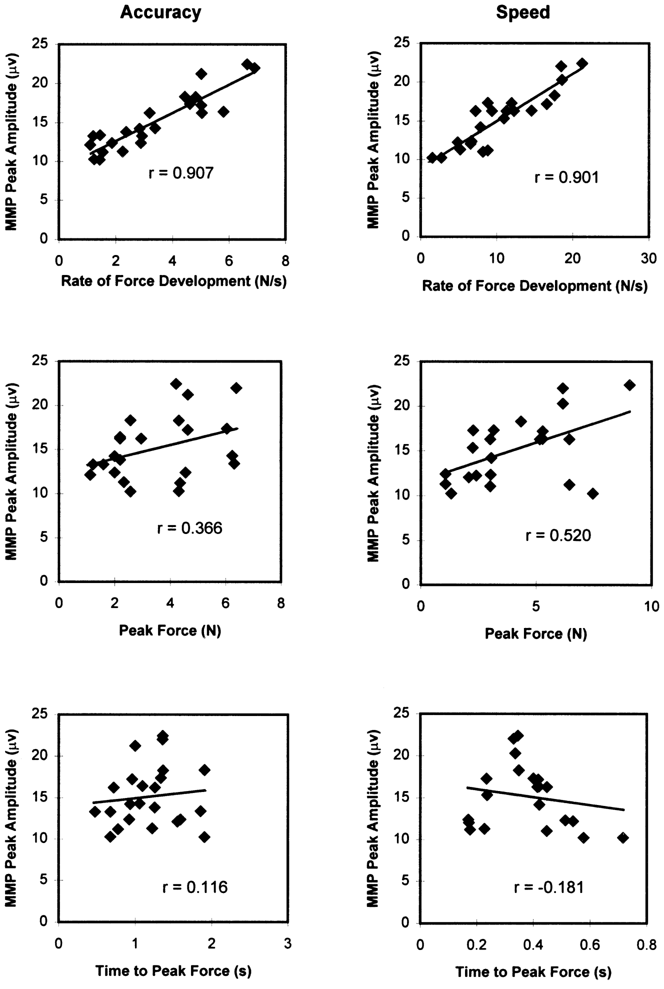

Fig. 8 Relationship of the movement-monitoring potential amplitude (mean based upon 25 trials) to rate of force development (Pf/Tp) for the first cycle, peak force, and time-to-peak force (all data averaged for 25 superimposed trials) for accuracy and speed conditions during repetitive task. Pearson pair-wise correlation coefficients (*r*) that are listed in legends of each plot are obtained based upon aggregated data for all 12 subjects and both right and left fingers. Best-fitting linear regression lines are superimposed on the scatter plots

and MP at contralateral sites in the tasks under both speed and accuracy instructions.

Discussion

This study investigated whether different speed and accuracy constraints in discrete and repetitive finger force-production tasks influence the characteristics of the MRP preceding and accompanying these tasks. There were two principal findings. First, there was a high positive correlation between MMP peak amplitude and the rate of force development for both repetitive and discrete tasks. And second, the amplitudes of MMP were consistently higher for force output performed under speed as compared to accuracy instruction. In addition, MRP onset times were generally earlier for the fast force output as compared to the accurate force output. The behavioral findings of this study demonstrate evidence of compliance with the speed-accuracy trade off (Fitts 1954, Meyer et al. 1990). As expected, under instructions of speed for both discrete and repetitive tasks, individuals were less accurate in their ability to produce exact forces than under instructions for accuracy. Further, instructions for speed and accuracy produced differential rates of force development, with the highest level being produced under speed instructions for both discrete and repetitive tasks (see also Gordon and Ghez 1987; Hancock and Newell 1985; Carlton et al. 1987). Speed and accuracy instructions, however, did not influence either force output or the coefficient of variation of force during the maintenance phase. In general, the behavioral data are consistent with traditional research in the area.

Consistent with previously reported findings (e.g., Kutas and Donchin 1974, 1980; Praamstra et al. 1995, 1996), our data of the grand mean MRP waveforms preceding self-paced right and left fingers for discrete force production tasks demonstrated differential activity at C3 and C4, contralateral to the finger used in the force output, regardless of the task requirements. A new finding in our work was the relationship between the amplitude of the MRP and rate of force development. Although Kutas and Donchin (1974) had reported a relationship between force and MRP components, ours is the first study to examine rate of force development. This is somewhat surprising, since rate of force development has been an important parameter in the behavioral literature. For example, the rate of force development has been shown to account for systematic changes in reaction time, while both peak force and force duration play secondary roles (Carlton et al. 1987). Our study demonstrated positive correlations between rate of force development and peak MMP amplitude for both speed (r=0.81) and accuracy (r=0.89) instructions during both discrete and repetitive tasks (r=0.91; r=0.90, respectively). This result was greatest at the site contralateral to the initial finger force-production. Further, the MRP onset times were also earlier at a higher rate of force development. Given that instructions for speed and accuracy were most successful behaviorally in inducing differences in rate of force development rather than force production itself, this would suggest that the differences in MRP amplitude and onset times, instead of being related to the selection of whole force output patterns or instructional constraints, would be related to the properties *intrinsic* to an initial force-time curve formation (i.e., the rate of force development). In other words, the amplitudes of MRP change during different force production tasks performed under speed and accuracy instructions would be directly related to the initial phase of the force-time curve formation. Of course, to answer this question, additional studies are needed that would directly manipulate rate of force development and target force levels while recording the EEG motor potentials and other physiological measures of cerebral activity. Such measures as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) would aid in determining specific areas of the motor system involved in force production. For example, Dettmers et al. (1995) correlated blood flow and force exerted, whereas Schlaug et al. (1996) used fMRI to study movement rate. This work could be also extended to examine rate of force development with cerebral activity. Thus, research is needed to further explore the notion that the *rate of force development* is one of the primary aspects of movements that connotes cortical representation of forthcoming overt motor activity.

A second finding from our study is that the amplitude of MRP was consistently higher for fast, rather than accurate, force output patterns. Further, the onset times of the MRP begin earlier for the fast force output than for the accurate force output. This is not what one might have expected considering past research has shown that accurate movements (which one might assume to be more complex) would generate higher MRP amplitude than would less accurate and therefore less complex movements (Schreiber et al. 1983; Benecke et al. 1985; Deecke 1990). However, there are also studies suggesting that higher MRP amplitudes occur under fast instructions, which require faster movement rates (Cooper et al. 1989; Wallenstein et al. 1995). It has also been shown that amplitudes of the MRP are higher in *ballistic* as compared to *ramp* movements. This suggests an association between MRP amplitude and the rate of force change as hypothesized by Grünewald and Grünewald-Zuberbier (1983a, b). Given the nature of the experimental design we used in this study, it is likely that during the speed task the accuracy components may have influenced the properties of the MRP. This is because the subjects would have used the graphical display of their force-production output with respect to the target force.

One important feature in the present study was the lack of correlation between BP and rate of force development as might be suggested by previous work (e.g., Kutas and Donchin 1974). Furthermore, as compared to MMP, BP did not change as a function of the four tasks. There are a variety of possible explanations that should be considered. The most obvious is that the current task duration which required continuous visual feedback, was longer than that of previous studies. This apparent disparity may also be due to the fact that subjects in this experiment were required to use visual feedback throughout the trial. In other words, the task execution and the presentation of the stimulus was presumably simultaneous, thus, subjects anticipated the feedback stimulus when preparing the force output. Therefore, the lack of a correlation with rate of force development might be due to *stimulus-preceding negativity* (Brunia 1988). This is in agreement with a number of studies (Brunia 1988; Brunia and Damen 1988; van Boxtel 1994) that revealed a right-hemisphere preponderance of the stimulus-preceding negativity independent of movement side and contralateral preponderance for the BP preceding the button press. Another possibility is that direct analysis of BP may obscure differences which other techniques (e.g., lateralized readiness potentials) might not. We are currently directing more systematic research at these questions.

Overall, the present study further demonstrates that electrocortical activity recorded from the scalp reflects preparatory processes for initiation of force output. We found differential effects of force production task (i.e., discrete versus repetitive) and task requirements (i.e., speed versus accuracy of force production) on the spatiotemporal and amplitude characteristics of the MRP. Further, beginning with results which show that differences in MRP amplitudes and onset times are related to the selection of more or less complex movement (or force production) patterns (Deecke and Kornhuber 1978; Benecke et al. 1985) and modulated by the modes of movement selection (Praamstra et al. 1995, 1996), the present study demonstrates the importance of an additional dynamic property of force-production preparation, that of rate of force development. Indeed, the rate of force development in our study was highly associated with spatiotemporal distribution and the magnitude of the movement-related potentials regardless of task (discrete or repetitive) or instruction set (speed or accuracy). As such this represents a controllable and representational variable in the production of finger force output. This is in accordance with the notion that motor activity, which includes the intention to initiate a planned action and reach a desired goal, is controlled by a limited number of parameters (Bernstein 1967; Enoka 1983; Gordon and Ghez 1987) reflected in MRP amplitudes and onset times. The full articulation of MRP with rate of force development awaits more systematic experimentation.

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References

Alexander G, Crutcher MD (1990) Neural representation of the target (goal) of visually guided arm movements in three motor areas of the monkey. J Neurophysiol 64:133–150

Ashe J (1997) Force and the motor cortex. Behav Brain Res 86:1–15

Becker W, Kristeva R (1980) Cerebral potentials to various force deployments. Prog Brain Res 54:189–194

Becker W, Iwase K, Jurgens R, Kornhuber HH (1976) BP preceding voluntary slow and rapid hand movements. In: McCallum WC, Knott JR (eds) The response brain. Wright, Bristol, England, pp 99–102

Benecke R, Dick JPR, Rothwell JC, Day BL, Marsden CD (1985) Increase of the Bereitschaftspotentials in simultaneous and sequential movements. Neurosci Lett 62:347–352

Bernstein N (1967) Coordination and regulation of movements. Pergamon Press, Oxford

Birbaumer N, Elbert T, Canavan A, Rockstroh B (1990) Slow potentials of the cerebral cortex and behavior. Physiol Rev 70:1–41

Boxtel G van (1994) Non-motor components of slow brain potentials. University Press, Tilburg

Brunia CHM (1988) Movement and stimulus preceding negativity. Biol Psychol 26:165–178

Brunia CHM, Damen EJP (1988) Distribution of slow brain potentials related to motor preparation and stimulus anticipation in a time estimation task. EEG Clin Neurophysiol 69:234–243

Carlton LG, Carlton MJ, Newell KM (1987) Reaction time and response dynamics. Q J Exp Psychol 39A:337–360

Cooper R, McCallum WC, Cornthwaite SP (1989) Slow potential changes related to the velocity of target movement in a tracking task. EEG Clin Neurophysiol 72:232–239

Deecke L (1990) Electrophysiological correlates of movement initiation. Rev Neurol 164:612–619

Deecke L, Kornhuber HH (1978) An electrical sign of participation of the mesial "supplementary" motor cortex in human voluntary movement. Brain Res 159:473–473

Deecke L, Grözinger B, Kornhuber HH (1976) Voluntary finger movements in man: cerebral potentials and theory. Biol Cybern 23:99–119

Deecke L, Eisinger H, Kornhuber HH (1980) Comparison of Bereitshaftspotential, pre-motion positivity, and motor potential preceding voluntary flexion and extension movement in man. Prog Brain Res 54:171–176

Dettmers C, Fink GR, Lemon RN, Stephan KM, Passigham RE, Silversweig D, Holmes A, Ridding MC, Brooks DJ, Frackowiak RS (1995) Relation between cerebral activity and force in the motor areas of the human brain. J Neurophysiol 74:802–815

Enoka RM (1983) Muscular control of a learned movement: the speed control system hypothesis. Exp Brain Res 51:135–145

Evarts E (1968) Relation of pyramidal tract to force exerted during voluntary movement. J Neurophysiol 31:14–27

Fitts RM (1954) Information capacity of the human motor system in controlling the amplitude of movement. J Exp Psychol 47:381–391

Foit G, Grözinger B, Kornhuber HH (1983) Brain potential differences related to programming, monitoring and outcome of aimed and nonaimed, fast and slow movements to a visual target: the movement monitoring potential (MMP) and the task outcome evaluation potential (TEP) (abstract). Neuroscience 34:571

Georgopoulos AP (1991) Higher order motor control. Annu Rev Neurosci 14:361–377

Georgopoulos AP, Ashe J, Smyrnis N, Taira M (1992) The motor cortex and the coding of force. Science 256:1692–695

Gerloff C, Toro C, Norimichi U, Cohen L, Leocani L, Hallett M (1997) Steady-state movement-related cortical potentials: a new approach to assessing cortical activity associated with fast repetitive finger movements. EEG Clin Neurophysiol 10:103–113

Gibson AR, Houk JC, Kohlerman NJ (1985) Relation between red nucleus discharge and movement parameters in trained macaque monkeys. J Physiol (Lond) 358:551–570

Gordon J, Ghez C (1987) Trajectory control in targeted force impulses. II. Pulse height control. Exp Brain Res 67:241–252

Grünewald G, Grünewald-Zuberbier E (1983a) Cerebral potentials during voluntary ramp movement in aiming task. In: Gaillard AWK, Ritter W (eds) Tutorial in ERP research: endogenous components. North-Holland, Amsterdam, pp 311–327

Grünewald G, Grünewald-Zuberbier E (1983b) Cerebral potentials during skilled slow positioning movements. Biol Psychol 31:71–78

Grünewald-Zuberbier E, Grünewald G (1978) Goal-directed movement potentials of human cerebral cortex. Exp Brain Res 33:135–138

Hancock K, Newell K (1985) The movement speed-accuracy relationship in space time. In: Aleur H, Kleinbeck U, Schmidt KH (eds) Motor behavior: programming control and acquisition. Springer, Berlin Heidelberg New York, pp 153–188

Hazemann P, Metral S, Lille F (1978) Influence of physical parameters of movement (force, speed and duration) upon slow cortical potentials in man. In: Otto DA (ed) Multidisciplinary perspectives in event-related brain potential research. US Government Printing Office, Washington DC, pp 107–111

Hepp-Reymond MC, Maier MA (1991) Central and peripheral control of dynamics in finger movements and precision grip. In: Requin J, Stelmach JGE (eds) Tutorial in motor neuroscience. Kluwer Academic, Netherlands, pp 517–522

Hocherman S, Wise SP (1990) Trajectory-selective neuronal activity in the motor cortex of rhesus monkeys (*Macaca mulatta*). Behav Neurosci 104:495–499

Jackson JH (1889) On the comparative study of diseases of the nervous system. BMJ 2:355–362

Jasper HH (1958) The ten-twenty electrode system of the International Federation. EEG Clin Neurophysiol 1:371–375

Kalaska J, Crammond D (1992) Cerebral cortical mechanisms of reaching movements. Science 255: 1517–1523

Kornhuber HH, Deecke L (1965) Hirnpotentialanderungen bei Willkurbewegungen und passiven Bewegungen des Menschen. Bereitschaftspotential und reafferente Potential. Pflugers Arch 284:1–17

Kristeva R (1984) Bereitschaftpotential of pianist. Ann NY Acad Sci 425:477–482

Kristeva R, Keller E, Deecke L, Kornhuber HH (1979) Cerebral potentials preceding unilateral and simultaneous bilateral finger movements. EEG Clin Neurophysiol 47:229–238

Kristeva R, Cheyne D, Lang W, Lindinger G, Deecke L (1990) Movement-related potentials accompanying unilateral and bilateral finger movements with different inertial loads. EEG Clin Neurophysiol 74:10–418

Kutas M, Donchin E (1974) Studies squeezing: the effects of handedness. The responding hand and response force on the contralateral dominance of readiness potential. Science 186:545–548

Kutas M, Donchin E (1980) Preparation to respond as manifested by movement related brain potentials. Brain Res 202:95–115

Lang W, Zilch O, Koska C, Lindinger G, Deecke L (1989) Negative cortical DC shifts preceding and accompanying simple and complex sequential movements. Exp Brain Res 74:99–104

Lang W, Obrig H, Lindinger G, Cheyne D, Deecke L (1990) Supplementary motor area activation while tapping bimanually different rhythms in musicians. Exp Brain Res 79:504–514

Meyer DE, Smith JEK, Kornblum S, Abrams RA, Wright CE (1990) Speed-accuracy tradeoffs in aimed movements: toward a theory of rapid voluntary action. In: Jeannerod M (ed) Attention and performance XIII. Erlbaum, Hillsdale, NJ, pp 173–226

Mushiake H, Inase M, Tanji J (1990) Selective coding of motor sequences in the supplementary motor area of the monkey cerebral cortex. Exp Brain Res 82:208–210

Niemann J, Winker T, Hufschmidt A, Lucking CH (1994) The influence of hand movements on cortical negative DC potentials. In: Heinze H-J, Munte TF, Mangun GR (eds) Cognitive psychophysiology. Birkhäuser, Boston, pp 265–287

Newell KM, Carlton LG (1985) On the relationship between peak force and peak force variability in isometric tasks. J Mot Behav 17:230–241

Oldfield RC (1971) The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9:97–113

Praamstra P, Stegeman DF, Horstink MWIM, Brunia CHM, Cools AR (1995) Movement-related potentials preceding voluntary movement are modulated by the mode of movement selection. Exp Brain Res 103:429–439

Praamstra P, Stegeman DF, Horstink MWIM, Cools AR (1996) Dipole source analysis suggests selective modulation of the supplementary motor area contribution to the readiness potential. EEG Clin Neurophysiol 98:468–477

Rockstroh B, Elbert T, Canavan A, Lutzenberger W, Birbaumer N (1989) Slow cortical potentials and behaviour. Urban & Schwarzenberg, Baltimore

Rouiller EM (1996) Multiple hand representation in the motor cortical areas. In: Wing AM, Haggard P, Flanagan JR (eds) Hand and brain: the neurophysiology and psychology of hand movements. Academic Press, San Diego, pp 99–122

Schieber MH (1996) Individuated finger movements: rejecting the labeled-line hypothesis. In: Wing AM, Haggard P, Flanagan JR (eds) Hand and brain: the neurophysiology and psychology of hand movements. Academic Press, San Diego, pp 81–96

Schlaug G, Sanes JN, Thangaraj V, Darby DC, Jancke L, Edelman RR, Warach S (1996) Cerebral activation covaries with movement rate. Neuroreport 7:879–883

Schreiber H, Lang M, Lang W, Kornhuber A (1983) Frontal hemispheric differences of the Bereitschaftspotential associated with writing and drawing. Hum Neurobiol 49:213–226

Stagliano N, Baran E, Kresch, E, Freedman W (1991) Quantitative analysis of the Bereitschaftspotential (abstract). Muscle Nerve (September) 985

Wallenstein G, Nash AJ, Kelso JAS (1995) Frequency and phase characteristics of slow cortical potentials preceding bimanual coordination. EEG Clin Neurophysiol 94:50–59

Wilke JT, Lansing RW (1973) Variations in the motor potential with force exerted during voluntary arm movements in man. EEG Clin Neurophysiol 35:259–265

Wing AM, Haggard P, Flanagan JR (1996) Hand and brain: the neurophysiology and psychology of hand movements. Academic Press, San Diego