STABILIZATION OF THE TOTAL FORCE IN MULTI-FINGER PRESSING TASKS STUDIED WITH THE 'INVERSE PIANO' TECHNIQUE

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INTRODUCTION

One of the central problems in motor control is the problem of motor redundancy [1]. This problem emerges when the number of variables at a selected level of analysis is higher than the number of constraints defined by the task such that an infinite number of solutions are possible. Recently, this problem has been addressed using the concept of a synergy as a neural organization of elemental variables that stabilizes a required value (or time profile) of a potentially important performance variable by co-varying adjustments of the elemental variables [2].

When one finger changes its force, other fingers of the hand can show unintended force changes either in the same direction, called enslaving [3, 4, 5], or in the opposite direction, called error compensation [6, 7]. We tested a hypothesis that externally imposed changes in finger force predominantly lead to error compensation effects in other fingers thus stabilizing the total force. A novel device, the "inverse piano" (IP), was used to impose controlled displacements to one of the fingers over different levels of displacement magnitudes and rates.

METHODS

Ten male subjects participated in the study. The IP device (Fig. 1) consisted of four uni-directional force sensors mounted on linear actuators that could produce smooth movements in the vertical direction. The collection of force data and control of device was done using custom made LabVIEW software. The task was to press naturally with all four fingers to match a target force on a computer monitor for the first 5 s. Force feedback was removed for the next 5 s, at which point one of the force sensors was unexpectedly raised and lowered back to its initial position. Force feedback and target force then were returned to the monitor for the remaining 3 s. Subjects were told return to the target force, if they had deviated during the non-feedback phase. The instruction given during key raising was to "don't pay attention to changes in finger forces, rather maintain the same effort of fingers as prior to the perturbation." The target force was scaled to measured values of maximum voluntary contraction (MVC), which were collected at the beginning of the experiment. Surface electromyogram (EMG) was recorded from the flexor digitorum superficialis (FDS) during trials. EMG was collected to determine whether there was a change in muscle activity during key raising.

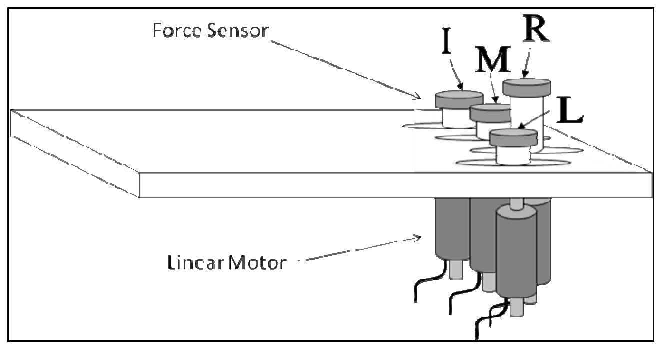

Figure 1: Schematic of the inverse piano device.

The final vertical displacement of key raised, speed of key raising, initial pressing force, and finger raised were the experimental variables. Two levels of final vertical displacement (1 cm and 2 cm), speed (1 cm/s and 3 cm/s), and initial target pressing force (5 % MVC and 20 % MVC) were used. There were four levels of finger raised (I, M, R, L).

The data of interest were the change in finger forces during the key raising. The change in finger force was defined as the difference between finger forces at the end of motor movement (to the raised position) minus the background force at the beginning. For each trial the force changes were calculated for all four fingers. The finger force changes were computed in terms of magnitude of force change and percent MVC of a given finger.

The force changes were then analyzed in several ways. First, for each combination of displacement, MVC, and speed, the data were averaged across subjects. Averaging was not performed across fingers. Further data analysis was performed on the sum of all finger force changes and the effect of proximity of non-raised fingers to the raised finger on their force change.

A four-way repeated measures MANOVA was performed to test for the effects of INITIAL FORCE (2 levels: 5% and 20%), DISPLACEMENT (2 levels: 1 cm and 2 cm), SPEED (2 levels: 1 cm/s and 3 cm/s), and FINGER (4 levels: I, M, R, and L). The responses tested were change in raised finger force, in terms of both N and % MVC, change in total non-raised finger force, change in total force (sum of individual finger force changes), and the % compensated values for each trial. A paired t-test was used to evaluate the difference in average EMG amplitude before and during key movement. To check whether proximity effects were significant a one-way ANOVA with three levels of proximity was applied.

RESULTS AND DISCUSSION

The force exerted by the raised finger always increased. The changes were from 1.39 ± 0.13 N (R-finger, INITIAL FORCE 5% of MVC, DISPLACEMENT 1.0 cm, SPEED 1.0 cm/s) to 8.00 ± 1.00 N (L-finger, INITIAL FORCE 20% of MVC, DISPLACEMENT 2.0 cm, SPEED 3.0 cm/s). In percent of the MVC, the changes ranged from 4.66 ± 0.38 % (I-finger, INITIAL FORCE 5% of MVC, DISPLACEMENT 1.0 cm, SPEED 1.0 cm/s) to 31.88 ± 2.19 % (L-finger, INITIAL FORCE 20% of MVC, DISPLACEMENT 2.0 cm, SPEED 3.0 cm/s). All the main effects, with the exception of the SPEED effect on the FORCE and % of the MVC change were statistically significant. There was no significant difference in muscle activity (EMG) during and before the key movement.

In all trials the total force of the non-raised fingers decreased. Hence, synergic mechanisms favoring negative force co-variation dominated over possible finger enslaving. The force changes ranged from –9.12 ± 1.49 N (L-finger, INITIAL FORCE 20% MVC, DISPLACEMENT 2.0 cm, SPEED 1.0 cm/s) to –0.29 ± 0.10 N (I-finger, INITIAL FORCE 5% MVC, DISPLACEMENT 1.0 cm, SPEED 1.0 cm/s). On a finger by finger comparison, the higher INITIAL FORCE level always resulted in a larger decrease in the total force of the non-raised fingers. For all other factors (FINGER, INITIAL FORCE, SPEED) being equal, the larger DISPLACEMENT level also always resulted in a larger decrease in the force of non-raised fingers. SPEED did not have a significant effect on the non-raised finger forces ($p > 0.50$). The proximity effect was found to be significant ($p < 0.005$) and showed a trend of a larger negative change in force by non-raised fingers with closer proximity to the raised finger.

Table 1: Statistical results on effect of experimental factors on finger force changes. P-values are given and significant values bolded.

Factor	Δ Raised Finger Force	Δ Non-Raised Finger Forces	Δ Total Force
INITIAL FORCE	**0.001**	**0**	**0.041**
DISPLACEMENT	**0.004**	**0.002**	0.845
SPEED	0.118	0.139	0.065
FINGER	**0.008**	**0.012**	0.255

CONCLUSIONS

The experiment produced two main results, reproducible across subjects: 1) a positive force change of raised finger and 2) a negative force change of non-raised fingers. In summary, these results showed that finger force adjustments during lifting of one of the fingers were dominated by synergic effects, not enslaving effects. These adjustments reduced the effects of the force change of the raised finger on total force, which may be interpreted as stabilization of the total force. We observed no signs of voluntary intervention by the subjects and hence interpret the data as resulting from involuntary synergic adjustments of finger forces.

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