EFFECTS OF CONTACT SURFACE PROPERTIES ON MULTI-FINGER FORCE PRODUCTION TASKS IN HUMANS

Jiseop Lee[1], Jihyun Ko[1], Siddhartha Bikram Panday[1], Kitae Kim[1], Jaebum Park[1,2]

Department of Physical Education, Seoul National University, Seoul South Korea[1]
Institute of Sport science, Seoul National University, Seoul, Korea[2]

The purpose of the current study was to investigate the effect of contact surface properties, which presumably determine the level of stimulation on the cutaneous receptors, on multi-finger force production and synergic actions of finger forces. The framework of the uncontrolled manifold (UCM) hypothesis was used to quantify indices of multi-finger synergies stabilizing total force in normal and tangent directions as well as the direction of resultant force (i.e., force angle) during steady-state force production. There was significant effect of contact surface on the magnitude of maximal voluntary contraction force. Also, there was a significant effect of the contact surface on the indices of force-direction (i.e., force angle) stabilizing synergies meaning that the stimulation on the cutaneous receptors could be an effective way to enhance the ability to organize the direction of finger forces.

KEY WORDS: cutaneous feedback, multi-finger synergy, contact surface property

INTRODUCTION: Many daily manipulation tasks require multiple digits to be used; the interactions between the digits should be controlled by the central nervous system (CNS) in a synergistic manner for the required tasks. When humans manipulate an object using their hands, the cutaneous feedback from the digits provide pivotal information to the CNS. It has been revealed that a removal of cutaneous feedback was detrimental to fine motor performance (Witney, Wing, Thonnard, Smith, 2004) and leads to a decrease in the maximal voluntary contraction forces (Shim, Karol, Kim, Seo, Kim, Kim, Yoon, 2012). Therefore, it is considered that the stimulation of the cutaneous receptors may have a positive effect on the finger force production and control. The purpose of the current study was to examine the effect of contact surface properties. Furthermore, the study may provide basis for fundamental researches in the field of sports which requires maximal force production, movement coordination, and sport equipment design. We explored finger interaction and multi-finger synergies based on the principle of motor abundance and using the framework of the uncontrolled manifold hypothesis (Scholz, Schöner 1999). The synergy is defined as a task-specific co-variation of elemental variables (commands to fingers) that stabilizes a performance variable (total force or force direction produced by the fingers).

METHODS

Subjects: 8 healthy young male subjects (age: 27.5 ± 5.7) were recruited. All subjects were right-handed and reported no neurological disorders that influence hand and finger motions.
Equipment: Three six-component force/moment transducers were used to measure individual finger forces of three fingers (i.e., index, middle, and ring fingers) in both normal (pressing) and shear directions.
Experimental procedures: The dominant hands of the subjects were tested under two contact conditions: 1) control condition with 320-grit sand paper (Fig. 1A), and 2) acupressure pad (particle diameter 2.5mm, Fig 1B) with two force direction conditions: 1) down and 2) down-left (Fig. 2). The experiment consisted of three blocks for each condition and each subject. First, single-finger and three-finger maximal voluntary contraction (MVC) tasks in both normal and shear directions were performed. The subjects had 8 s to reach the maximum force level. The maximal total force (MVC_{IMR}) and the individual finger forces (MVC_i; i = {*index, middle, ring*}) were computed at the time of MVC_{TOT}. Second, single-finger ramp tasks in downward (normal force) and down-left (normal force + shear force) directions were performed. During each trial, the subject was asked to press with one finger (i) and follow with that finger's force the template showing slanted line from 0% to 40% of MVC_i. Both the task and non-task finger forces were measured to quantify the indices of unintended force production by non-task fingers (i.e.,

enslaving).The third task required the subject to produce a steady-state force level while pressing naturally with all three fingers followed by a quick force pulse to a target. The force-feedback screen showed the initial force level (5 % of MVC_{TOT}) and the target force level (at 25 ± 5 % of MVC_{TOT}) shown in Fig. 2. For the first 5 s, the subject was required to match the initial force level. After 5 s, when the cursor staying within the circle of the initial force level, the subjects were instructed to produce a force pulse into the target at a self-selected time within next 5 s. The subject performed 25 trials for each condition with 10-s intervals between the trials.

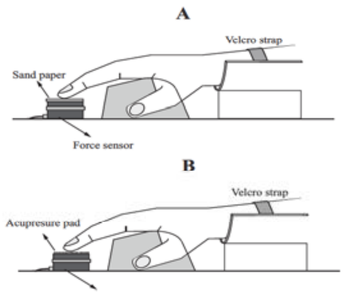

Figure 1. The experimental setup for finger force production tasks. **(A)** 320-grit sand paper and **(B)** acupressure pad were mounted on each force/moment sensor.

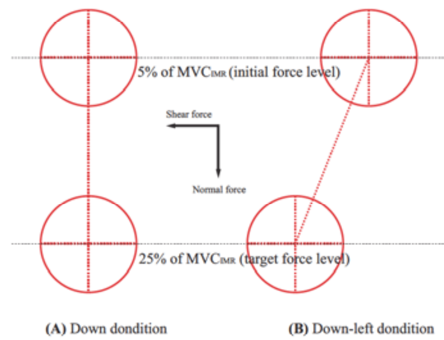

Figure 2. Feedback screen for (**A**) down and (**B**) down-left condition.

Analysis

The following outcome variables were quantified:

Force deficit (FD): the force difference between the sum of *MVC* forces of individual finger during single-finger task ($\sum MVC_i$) and the MVC force during three-finger task (MVF_{IMR}) (Eq. 1).

$$FD_i = ((\sum MVC_j) - MVC_{IMR}) / (\sum MVC_j) \times 100 \qquad \text{(Eq. 1)}$$

i = {normal and shear directions}, j = {index, middle, and ring}

*Finger force enslaving (EN): the enslaving matrix (**E**) which reflects the* involuntary force productions by non-task fingers (i.e., finger independency) during single-finger ramp tasks was constructed (Eq. 2).

$$E = \begin{bmatrix} k_{I,I} & k_{I,M} & k_{I,R} \\ k_{M,I} & k_{M,M} & k_{M,R} \\ k_{R,I} & k_{R,M} & k_{R,R} \end{bmatrix} \qquad \text{(Eq. 2)}$$

$$EN_j = \sum k_{i,j}/2 \ (i \neq j),\ i,j = \{\text{index, middle, and ring}\} \qquad \text{(Eq. 3)}$$

Further, an index of overall enslaving, EN_j (Eq. 3), which presents the average $k_{i,j}$ across the non-task fingers, was computed. Note that the smaller the *EN* value was, the larger the finger independency was.

Indices of multi-finger synergy: The time (t_0) of initiation of change in the apparent performance variable (F_{TOT}; resultant force of the three fingers) was defined as the time when the first derivative of force (dF/dt) reaches 5% of its peak value in that particular trial. The time to reach F_{PEAK} (t_{PEAK}) was defined as the time of F_{PEAK} with respect to t_0. The data from the repetitive trials were aligned with respect to t_0. Further analysis was used an index of multi-finger force stabilizing synergy computed within the framework of the uncontrolled manifold (UCM) hypothesis. After the trial alignment, variance in the force space across trials was quantified separately in two sub-spaces for each time sample. The first sub-space (UCM) corresponds to a fixed value of F_{TOT}. The second sub-space is the orthogonal complement to the first one. The two variance components (V_{UCM} and V_{ORT}) were further combined into a single metric, a synergy index, ΔV, which was computed for each time sample and form a time function:

$$\Delta V(t) = (V_{UCM}(t)/2 - V_{ORT}(t)/1)/(V_{TOT}(t)/3) \qquad \text{(Eq. 4)}$$

where each variance index was normalized by the number of degrees-of-freedom in the corresponding spaces; V_{TOT} stands for total variance. Note that $\Delta V > 0$ corresponds to

proportionally more variance within the UCM, which is interpreted as a synergy stabilizing selected performance variables. Larger positive values of ΔV may be interpreted as reflecting a stronger synergy. This was done to explore whether the central nervous system produces co-variation of finger forces to stabilize only resultant normal force, only resultant shear force, or both (i.e., force-angle).
Time of anticipatory synergy adjustment (t_{ASA}): The time of initiation of changes in ΔV_Z (time of anticipatory synergy adjustment, t_{ASA}) was defined as the time when ΔV_Z drops below its average steady-state value by more than two SDs. The average value and standard deviation (SD) of ΔV_Z was computed for the steady-state (between -600 and -400 ms before t_0). Negative values of t_{ASA} mean that ΔV_Z starts to drop before the initiation of F_{TOT} changes.
Statistics: ANOVAs with repeated measures were used to analyze the effect of contact surface conditions & force directions on the main outcome variables. Factors were *Finger* (3 levels: I, M, R), *Contact-surface* (2 levels: control, acupressure pad), and *Force-direction* (2 levels: down, down-left)

RESULTS

Maximal voluntary contraction (MVC) force: For the pressing force, MVC_{IMR} was increased with the acupressure pad as compared to the *MVC* during the control condition (on average, 78N at the acupressure condition; 56N at the control condition), while $\sum MVC_i$ between two conditions were not significantly different. For the shear force, the effect of the acupressure pad on MVC_{IMR} was not significant. However, $\sum MVC_i$ was decreased with the acupressure condition (on average, 21N at the acupressure condition; 28N at the control condition, $p< 0.05$).
Force deficit (FD): For both normal and shear forces, the force deficit (FD) was smaller in the acupressure pad condition than in the control condition ($p<0.05$, Fig. 3). In particular, the effect of the *Contact-surface* on the FD was stronger in the normal force than in the shear force.

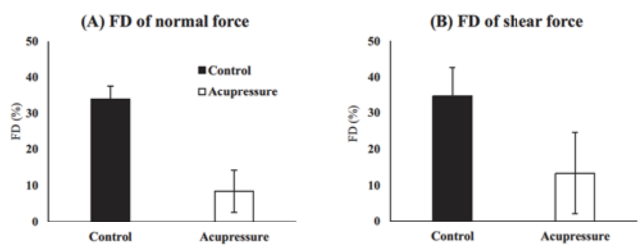

Figure 3. Force deficit (FD) in percentage (%) for **(A)** normal force and **(B)** shear force for control condition (black bars) and acupressure pad condition (white bars). Values are means ± standard errors

Enslaving (EN): The enslaving index of the index finger was smaller than the indices of middle and ring fingers regardless of contact conditions and direction of forces. No significant effect on the *EN* with the factors of *Contact-surface* and *Force-direction*.
Anticipatory synergy adjustment: In general, the synergy index (ΔV_Z) dropped prior to the initiation of force pulse in all conditions (on average, by about 230ms). The main effects of *Contact-surface* and *Force-direction* were not significant and no interaction effect.
Multi-finger synergy during the steady-state force production: For ΔV_Z of normal force, the main effects of *Contact-surface* and *Force-direction* were not significant (Fig. 4A). For ΔV_Z of shear force, the main effects of *Contact-surface* and *Force-direction* were not significant with a significant *Contact-surface × Force-direction* ($p< 0.05$, Fig. 4B). A significant *Contact-surface × Force-direction* interaction for the ΔV_Z of shear force reflected the fact that ΔV_Z was larger in 'down-left' task than in 'down' task, particular for the acupressure pad task. For ΔV_Z of force-angle, the main effect of *Contact-surface* was significant with a significant *Contact-surface × Force-direction* ($p< 0.05$, Fig. 4C).

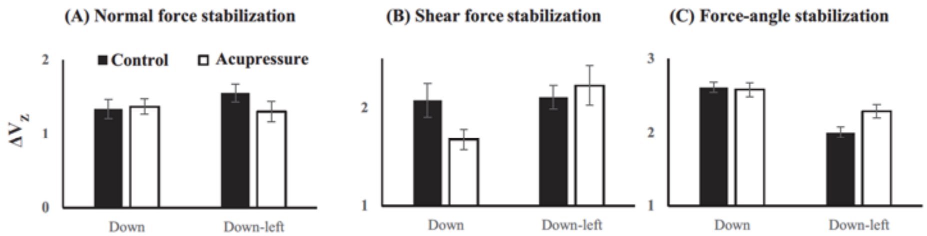

Figure 4. ΔV_Z for **(A)** normal force stabilization, **(B)** shear force stabilization, and **(C)** force-angle stabilization. The black and white bars represent control condition and acupressure pad condition, respectively. Values are means ± standard errors

DISCUSSION & CONCLUSION:

There were substantial increases in the maximal voluntary contraction forces of both normal and shear directions under the acupressure pad condition. In addition, the increased MVC forces were associated with the decreased force deficit in both normal and shear forces. However, the finger independency was not changed with the acupressure pad. Our results suggest that through stimulating the cutaneous receptor by the acupressure pad during finger pressing increased afferent inputs from the receptor, thereby the central commands regarding force production may be facilitated for all involved fingers resulting in the decreased force deficit (FD) and no change in the enslaving (EN). The anticipatory synergy adjustment represents the ability of feed-forward adjustment of the indices of synergy in anticipation of an upcoming action. It has been assumed that anticipatory synergy adjustments (ASA) affect the neural variables which are incorporated with stability properties of performance variables. In the current study, the ASA was not affected by the contact surface properties. Therefore, the central control signals in feed-forward adjustment may not be mediated by change in strength of stimulation on the cutaneous receptors. However, the current results indicated that the stimulation on the cutaneous receptors could be an effective way to enhance the ability to organize the direction of end-effector forces (i.e., larger ΔV_Z of force-angle in the acupressure pad condition). The outcomes of the current study can be used as a basis for further fundamental researches for examining the effect of surface properties on cutaneous receptors for enhancing performance especially in the field of sports. In other words, it is considered that researchers can gain insight on how detailed and precise control of finger forces varies in sports such as archery, shooting, rock climbing etc (Macleod, 2007).

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