5-2015

Effect of Absent Tactile Sensation on Multi-digit Coordination Underlying Hand Control

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This manuscript has been read and accepted for the

Graduate Faculty in Physical Therapy in satisfaction of the

capstone project requirement for the degree of DPT

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ABSTRACT

EFFECT OF ABSENT TACTILE SENSATION ON MULTI-DIGIT COORDINATION UNDERLYING HAND CONTROL

BY

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We investigated the effect of anesthesia, causing absent tactile sensation feedback, on multi-digit coordination underlying hand control. The purpose of the study is to expand our understanding on the essential role of tactile sensation feedback in the sensorimotor integration process by examining the motor coordination patterns during multi-digit forces production tasks. We hypothesized that absent tactile sensation feedback would interrupt the force sharing pattern at local and non-local digits. Twelve participants were utilized for data collection and statistical analysis (25.6 ± 4.1 years old, 6 males and 6 females), right-handed (according to their preferred hand use for writing and eating) and had no significant hand injury within the last five years. All participants performed a maximal voluntary contraction (MVC), ramp, and step task, pre- and post-anesthesia. In general, participants presented lower maximal force production in all MVC conditions after anesthesia, total MVC force was not distributed evenly among individual digits, and when sensory function of the MVC involved digits are uniformly absent or intact, force sharing pattern across the individual digits would be maintained. When the instructed finger (master finger) was index, other fingers (enslaved fingers) barely produced force. However, other enslaved fingers showed relatively higher forces when the master finger was ring or little finger. When required force level increased, performance error was increased accordingly. The

findings from the current study confirmed our hypothesis that absent tactile sensation feedback (somatosensory feedback) will not only affect force production at local digits, but also at non-local digits as well.

ACKNOWLEDGEMENTS

Dr. Wei Zhang, PhD, MS for her guidance and mentorship through the past three years in the research section of the doctor of physical therapy program at the College of Staten Island. Dr. Cynthia L. Benson and Dr. Barry Hahn, DO, Emergency Medicine, Staten Island University Hospital for their time, resources, and willingness to help in the current study. All participants, for their involvement and cooperation in our research.

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INTRODUCTION

The hand is essential to human motor behavior and its performance in an incredible range of manipulative behaviors. The hand and the grasping ability of its digits, play a crucial role in everyday tasks such as grabbing a mug, turning a doorknob, inserting a key, operating tools, and using it for artistic expression. This complex motor system and its dexterous manual tasks require complex spatial and temporal coordination of the digits that can be flexibly adapted to object properties such as weight, friction and center of mass. Such delicate multi-digit coordination can be learned through the integration of feedback signals from visual, tactile, and proprioceptive (muscle and joint receptors) information and the task-specific motor command from central nervous system (CNS) (Gordon et al. 1993).

Hand-object interactions allow the formation of sensorimotor memories of the object properties such as mass and its distribution (Zhang et al. 2010, 2011) and the exquisite digit force coordination necessary to manipulate it (Augurelle et al. 2003, Santello and Soechting 2000, Zhang et al. 2009). Appropriate modulation of forces, either within- or across-digits, relies on responses triggered by tactile feedback (Macefield et al. 1996). In addition to the above described role of sensory information for the formation of sensorimotor memories, tactile feedback has been found to be responsible for triggering short-latency force adjustments as a result of perturbations (Hermsdorfer et al. 1999; Macefield et al. 2003) or when digit forces are erroneously planned (Edin et al. 1992; Flanagan and Wing 1997). Such short-latency force responses, however, are absent or delayed when the tactile sensation is blocked (e.g., under digital anesthesia), and subsequently reduced excessively during large grip forces in manipulative tasks (Monzee et al. 2003). Even though the digit forces modulation across different manual tasks has been extensively studied (Cole et al. 2003, Jenmalm and Johansson

1997, Rearick and Santello 2002, Santello and Soechting 2000; Salimi et al. 2000 Smith and Soechting 2005), role of tactile sensation feedback in the sensorimotor integration underlying hand control is not well understood. In this scenario, temporarily blocking the digital sensory feedback would help to remove one link of tactile sensation from the sensorimotor integration chain, and thus contributes to its mechanism of process decoding.

Aoki et al. recently (2007) investigated the role of tactile information in the co-existence of cross-digit coordination and independent digit control, and found that changes in texture at a given digit elicit force adjustments at the same as well as other digits (‘local’ and ‘non-local’ responses), indicating that sensory information at one digit affects the force modulation at non-stimulated digits. Recent findings reported by Zhang et al. (2011, 2012, 2013, 2014) on sensorimotor integration in patients with carpal tunnel syndrome revealed that sensory functional deficit on a subset of digits lead to reduced ability in multi-digit force modulation, the extent to which is dependent on whether both sensory-intact and –impaired digits are involved in the object manipulation. These results imply that sensory information from one digit is shared across other digits to attain and maintain task-specific performance stability. This raised an important question regarding the “local” and “non-local” digital responses when the tactile sensation feedback used to sense object properties is completely blocked. Furthermore, what if the involved digits are not uniformly absent from tactile sensation, i.e., tactile sensation at some digits are unaffected? If so, how, and to what extent, would the CNS be able to integrate the partially affected sensation feedback into hand functional control?

In the present study, the effect of absent tactile sensory feedback by using digital anesthesia in the isometric pressing tasks will be investigated. Past studies, discussed above, have adopted two digit grip or multi-digit grasp protocol, in which not only sensation feedback within the digits, but beyond the digits (e.g., palm and wrist) might be recruited in the dynamic movement control process. The purpose of the study is to expand our understanding on the essential role of tactile sensation feedback in the sensorimotor integration process by examining the motor coordination patterns during multi-digit forces production tasks. The present project investigates the hypothesis that temporary loss of tactile sensation will interfere with sensorimotor learning and integration process, thus leading to 1) reduced ability of maximal force production in anesthetized digits; 2) different force sharing pattern at both affected and non-affected digits; and 3) diminished task performance in sub-maximal force production tasks.

METHODS

Subjects

Seventeen healthy individuals were recruited to participate in this experiment. Following introductory interviews and exclusion as determined by principal investigator and involved physician, twelve participants were utilized for data collection and statistical analysis (25.6 ± 4.1 years old, 6 males and 6 females). The weight and height of the participants averaged 81.3 ± 14.6 kg and 172.6 ± 10.1 cm respectively. All participants were right-handed (according to their preferred hand use for writing and eating) and had no significant hand injury within the last five years. The right hand width (measured at the metacarpophalangeal joint level) averaged 8.5 ± 1 cm, and the right hand length (measured from the midpoint of the transverse wrist crease to the tip of the middle finger) was 18.5 ± 1 cm. All participants were given individual consent forms according to the procedures approved by the Office for Research Protection of the College of Staten Island.

Apparatus

Four 6-dimentional force/torque sensors (nano 17, ATI Industrial Automation, NC) with the diameter of 1.5 cm were used to measure forces produced by each of the four fingers of the right hand. The sensors were medio-laterally distributed 30 mm apart within the frame. The position of the sensors within the frame could be adjusted in the forward-backward direction to fit the individual participant's hand anatomy. The force measured by each sensor was sampled at 1000Hz.

Anesthesia Procedure

Temporary removal of sensory feedback was performed on each participant. This was done to evaluate the effect of absent tactile sensation on a subset of digits during skilled manipulative behaviors. Anesthesia of fingertip tactile afferents were performed in the protocol to block the activity of superficial and deep cutaneous mechanoreceptors of index (I) and middle (M) fingers, but not at ring (R) and little (L) fingers. The anesthetic administered was a mixture of lidocaine (1%) and bupivacaine (0.5%) (50:50). Injection of lidocaine has been shown successfully blocked both superficial and deep mechanoreceptors (Jenmalm et al. 2000). The addition of bupivacaine prolongs the duration of the anesthesia effect to ~3 hours. Note that the thumb was not involved in the study protocol. Local sensation was temporarily removed ONLY for joints and muscles distal to the Metacarpal Phalangeal joint (MPJ) of the digit (in the web space), and therefore, sensory feedback remained intact for joints and muscles in the hand and forearm that were proximal to the MPJ. The digital anesthesia procedure was performed at the Staten Island University Hospital by a designated licensed physician.

Experimental Procedure

The experimental procedure involved all participants performing a pre-anesthesia, control trial, and post-anesthesia visit, with at least a two week interval between visits, in the current study. During the test, all participants were seated in a standard sized chair, facing the testing table with his/her right upper arm at approximately 45 degrees of abduction in the frontal plane and 45 degrees of flexion in the sagittal plane, the elbow at approximately 45 degrees of flexion. A custom-fitted wooden piece was placed underneath the subject's right palm to help maintain a constant configuration of the hand and fingers. Two Velcro straps were used to prevent forearm or hand motion during the tests. One more pair of Velcro straps ensured that the wooden piece was stable with respect to the board. A 21'' LCD monitor was placed approximately 65 cm in front of the participant. It displayed both task required force templates as well as participants' time-force performance profiles.

The participants were instructed on three isometric force production tasks (Figure 1, found in Appendix). The first task was to produce isometric fingertip press-down forces on the table to reach a maximal voluntary contraction (MVC task). The second and third tasks were to follow a target force-time template ('Ramp' like pattern and 'Step' like pattern) displayed on a computer monitor (Ramp task and Step task). The MVC test was performed by involving different combinations of digits to investigate the maximal voluntary contraction. This was performed under seven conditions, which included the MVC ability of all four digits separately (except Thumb), MVC ability of a subset of digits (index and middle vs. ring and little), as well as the MVC ability of all four digits combined. During the MVC tests, the participants were encouraged to produce as much force as possible by pressing down on the force sensors. Therefore, responses of the maximal force ability on 'local' and 'non-local' digits introduced by lack of tactile sensation could be further evaluated. Two MVC trials were performed by each subject, and the trial with larger maximal force was chosen to be analyzed in the study.

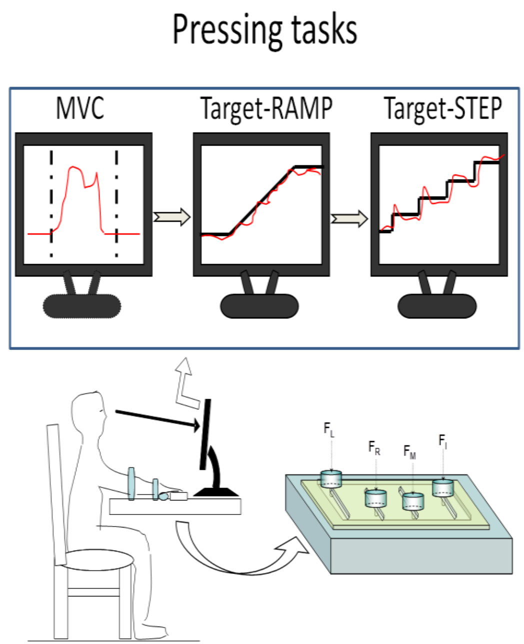


Figure 1: Experimental Procedure. Figure 1 is a pictographical representation of the design set up for all trials and all participants.

The Ramp task was performed by targeting all four digits separately. Participants were asked to follow a time-force task template displayed as a thick blue line in a ramp-like manner on the computer monitor. The task template was individualized according to individual subject's single finger maximal force tested in MVC task, including three components (i.e., a 1-s 0% MVC horizontal line, a 4-s 0-10% MVC ramp line, and a 1-s 10% MVC horizontal line). Each subject performed in total of four trials in ramp task by each individual finger (Index, middle, ring and little) respectively. Digit force performance denoted as a yellow line was also displayed to provide instant feedback for participants. The purpose of the Ramp task was performed in order to determine the digital force sharing patterns (Enslaving Effect) based on the individual forces across trial variability for each participant.

In the step task, participants were asked to follow a time-force task template displayed in a step-like manner on the computer monitor. The task template was individualized according to individual subject's four-finger maximal force tested in MVC task, including five components (i.e., a 1-s 0% MVC, a 3-s 2.5% MVC, a 3-s 5% MVC, a 3-s 7.5% MVC and a 10% MVC horizontal lines). Two conditions were involved in the Step tasks: four-finger condition (IMRL) and adding-finger condition (I+M+R+L). Four-finger condition was performed by utilizing all four digits at the same time, while the adding-finger condition required participants to start the step task with the index finger and progressively add each additional finger in a left-to-right direction as each 'Step' of the task was reached. In total of 25 trials were performed in each condition after 5 practice trials by each subject. This task was performed in order to evaluate motor performance and coordination in absence of local sensation feedback at a subset of digits. A 10 second and a 1 minute rest period were given between trials and tasks separately to prevent participants' fatigue.

DATA ANALYSIS

Maximal force in MVC task, force sharing patterns and enslaving matrix in Ramp task, and force performance error in Step task were evaluated before and after the anesthesia procedures. Multiple-way ANOVAS with repeated measures were performed to analyze the results. The following three factors were evaluated in the ANOVA tests: 1) *Group*, 2-way ANOVA, contained two levels (anesthesia and control), 2) *Condition*, separate 2-way ANOVA, (7 levels in the MVC task, and 2 levels in Step task), 3) *Digit*, 3-way ANOVA, contained four levels (I, M, R, L fingers) in Ramp task. All factors were within-subject factors.

RESULTS

Maximal Force in MVC Task

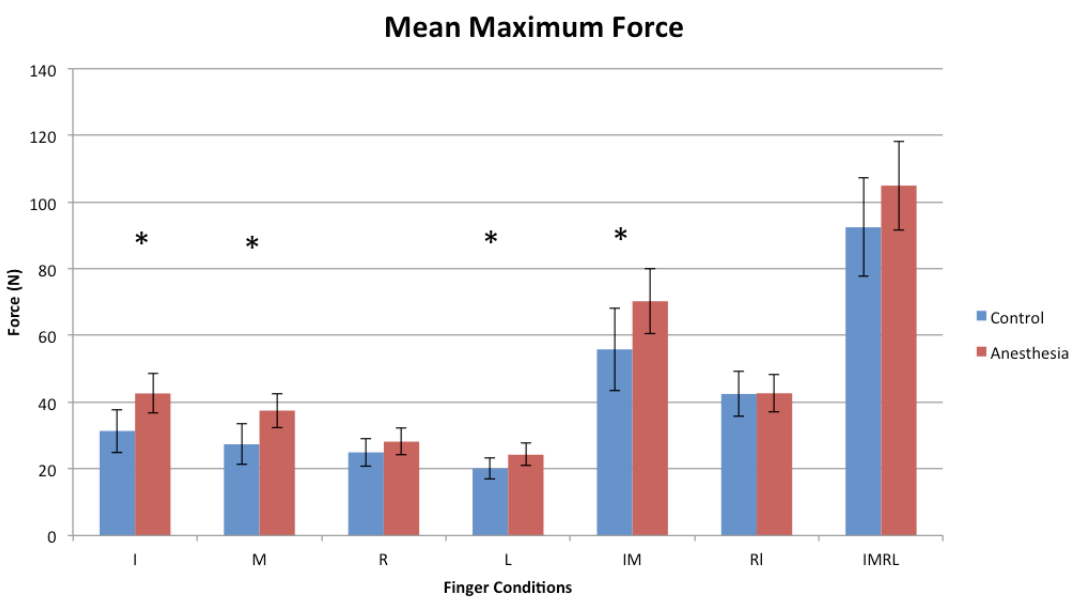


Figure 2: Mean Maximal Force. Comparison of average maximum force applied by control and anesthesia conditions: significant differences seen in I, M, L, and IM tasks.

In general, participants presented lower maximal force production in all MVC conditions after anesthesia (Figure 2). Specifically, digital maximal force was significantly decreased at index, middle and index-middle combination conditions under anesthesia. In addition, MVC forces of the L finger were found significantly decreased after anesthesia at index and middle finger. A lower MVC of L after the anesthesia procedure revealed that the non-local digit could respond to the removal of tactile sensation at local digits. These results were confirmed by a 2-

way ANOVA with repeated measures with factors of *Group* (Anesthesia vs. Control) and *Condition* (I, M, R, L, IM, RL, IMRL). Note that no group difference was found at all-digit condition.

Force Sharing in MVC Task

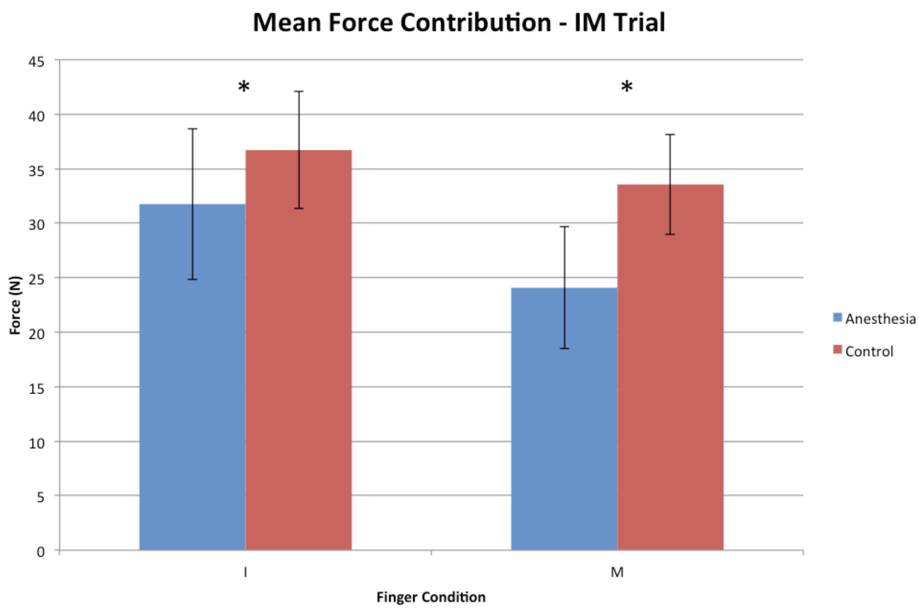


Figure 3: Mean Force Conribution – IM Trial. Total MVC force was not evenly shared between I and M, resulting in a significant difference between the force applied in each condition.

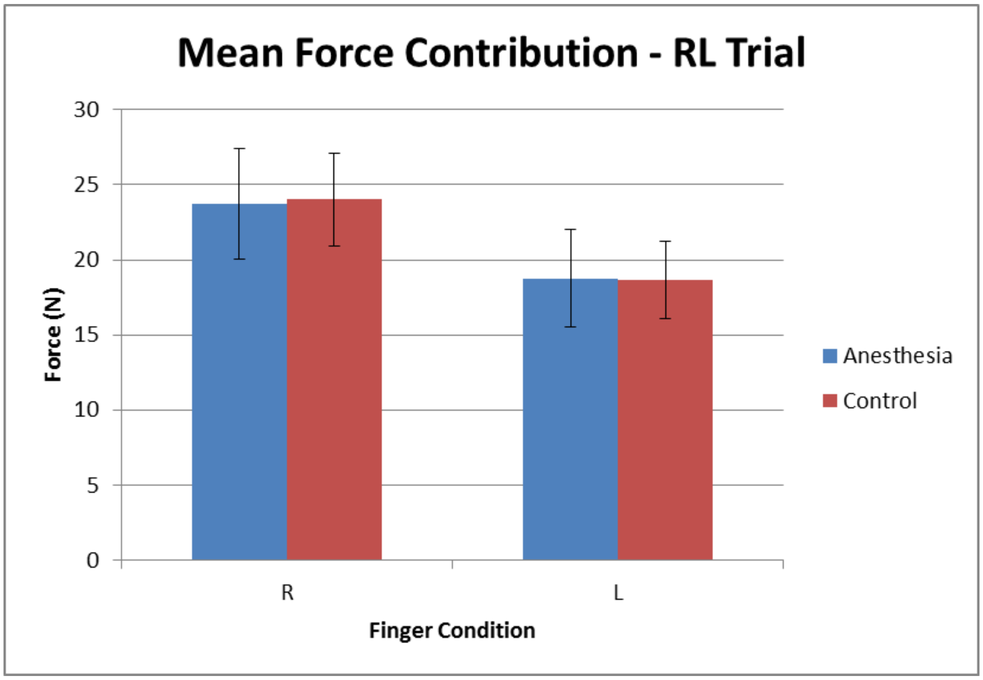


Figure 4: Mean Force Contribution – RL Trial. Comparison of average force applied in each condition, by each digit in R-L task. illustrating force shares at R and L showed none group difference.

When sensory function of the MVC involved digits are uniformly absent or intact, force sharing pattern across the individual digits would be maintained. The anesthesia induced total maximal force reduction, compared to the control, at the IM condition. Additionally, both involved digits (I, M), contributed to this total maximal force reduction (Figure 3). There was a group difference of the MVC at IM and the force shares at I and M, however, there was not a group effect of MVC at RL nor of force shares at R and L (Figure 4).

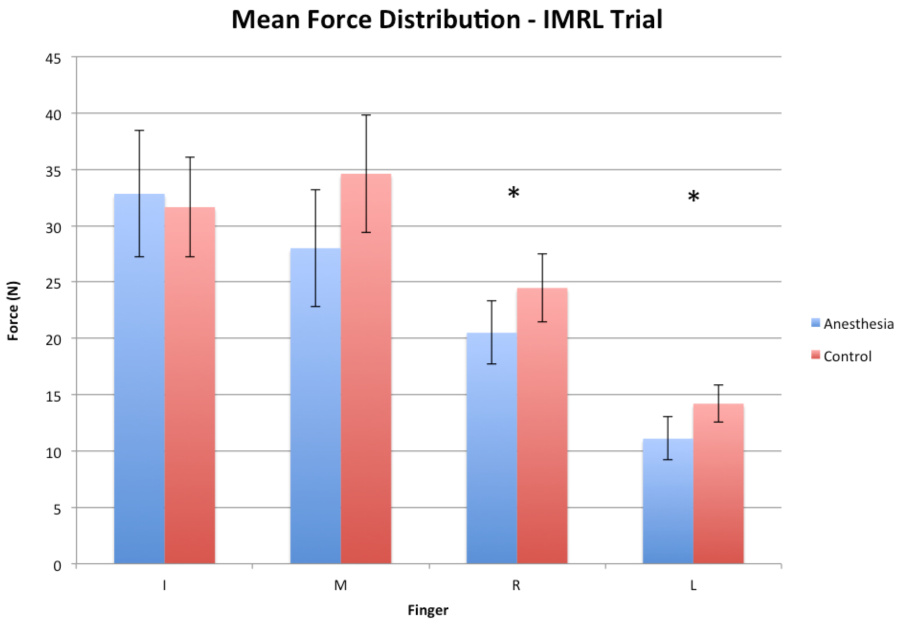


Figure 5: Mean Force Distribution – IMRL Trial. Average forces applied by each digit for each condition: a main effect of digits, I≈M>R>L.

Total MVC force was not distributed evenly among individual digits. There is a main effect of digit for all three conditions (IM, RL, IMRL). For the IM condition, I produces greater force than M (Figure 3). For the RL condition R produces greater force than L (Figure 4). For the IMRL condition, I produces a statistically similar force to M; both I and M produce greater force than R, which produces greater force than L (Figure 5).

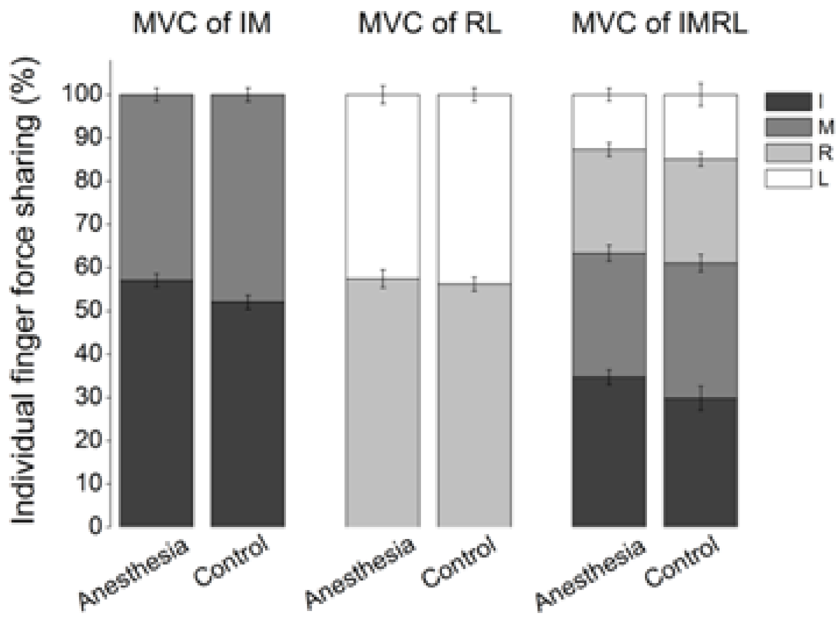
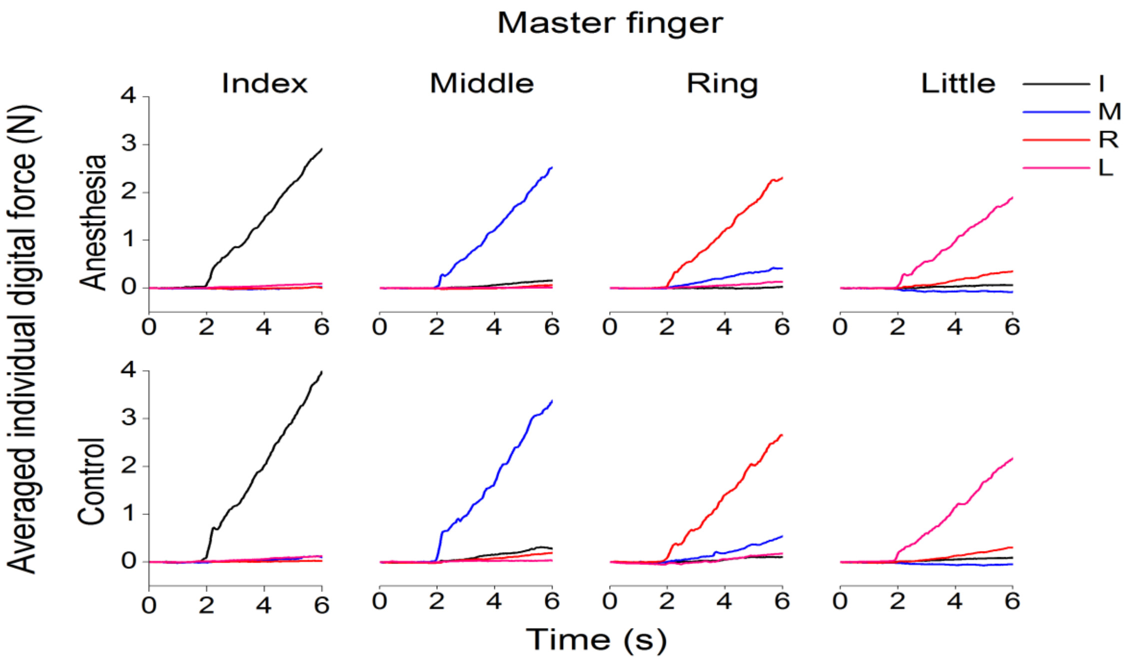


Figure 6: Distribution of Maximal Voluntary Contraction. MVC at IMRL condition, individual finger force observed at R and L fingers were significant lower after anesthesia procedure at I and M (i.e., interaction effect of group*digit at IMRL).

When tactile sensation feedback of the task-involving digits are not uniformly affected the total maximal force is re-distributed among the individual digits. This finding is observed as there is an interaction effect of group digit at IMRL (Figure 6). Individual finger force at R and L were significantly lower after the anesthesia procedure (which only affected I and M). However, the participants produced statistically similar MVC at the IMRL condition.

These results were confirmed by separate 2-way ANOVAs as performed with repeated measures with factors of *Group* (Anesthesia vs Control) and *Digit* (IM, RL and IMRL).

Enslaving Phenomena in Ramp Task



Figure

Figure 7: Average Enslaving Matrix. Average individual finger time-force profiles across participants in four conditions (columns) of Ramp task for both anesthesia and control groups.

When the instructed finger (master finger) was index in the Ramp task, other fingers (enslaved fingers) barely produced force, however, this is not true for other master finger conditions. Specifically, other enslaved fingers showed relatively higher forces when the master finger was ring or little finger (Figure 7). This observation has been confirmed by the 3-way ANOVA performed based on enslaving matrix with factors of *Group* (Anesthesia vs. Control), *Condition* (master finger of I, M, R, L), and *Enslavefinger* (i.e., three other fingers for each master finger condition) There is a main effect of condition ($F_{[3,33]}$ =7.73, $p<0.001$). Posthoc comparisons showed that enslaved fingers showed significantly lower forces in the I finger master condition, compared with those in the R finger master condition and L finger master condition.

Task Performance Error in Step Task

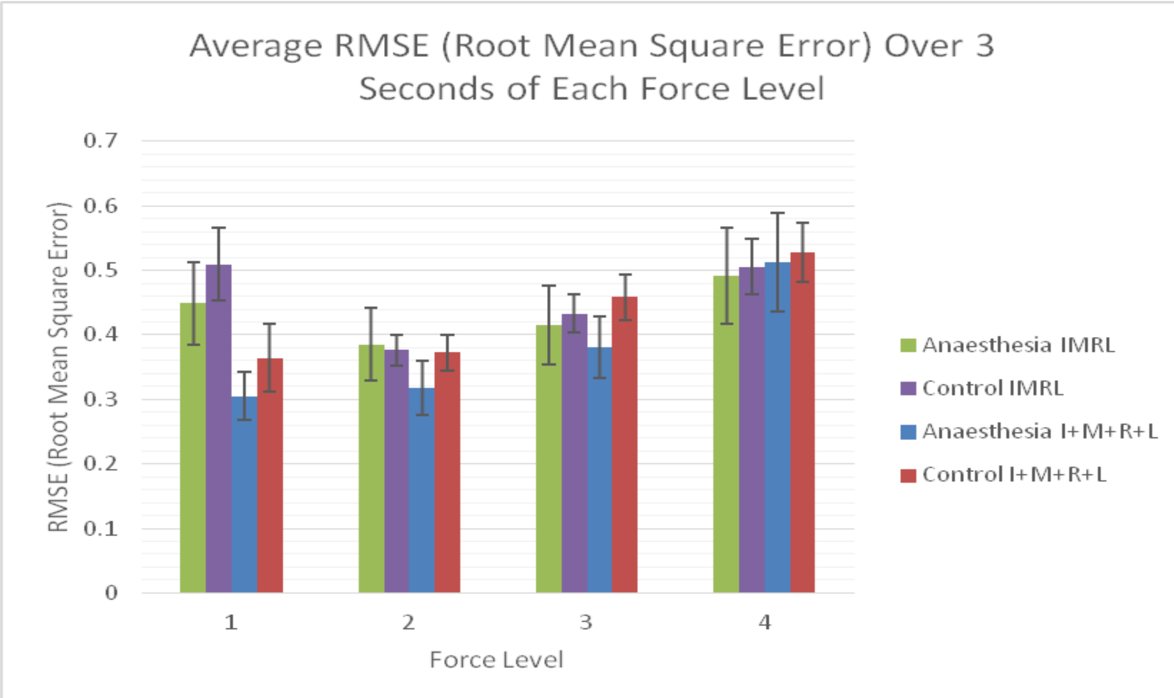


Figure 8: Average Root Mean Square Error. Averaged root mean square error in both Step task conditions across participants in anesthesia and control groups separately.

To evaluate participants force production performance accuracy relative to task-required target force, root mean square error was calculated for all force levels (i.e., steps) in Step task. In general, when required force level increased, performance error was increased accordingly. Additionally, participants presented larger RMSE in four-finger condition (IMRL) compared to the added-finger task (I+M+R+L) (Figure 8). However, no group difference was observed in participants' force production task performance. These findings can be confirmed by a 3-way ANOVA with repeated measures, with within-subject factors of *Group* (Anesthesia vs. Control), *Condition* (IMRL vs. I+M+R+L) and *Forcelevel* (2.5%MVC, 5%MVC, 7.5%MVC, 10%MVC). Both condition ($F_{[1,11]}$ =5.663, $p<0.05$) and forcelevel ($F_{[1.513,16.64]}$ =9.829, $p<0.005$) showed main effect on RMSE.

DISCUSSION

Effect of Digital Anesthesia in Hand Functional Control - Maximal Force Ability

The findings from the current study confirmed our hypothesis that absent tactile sensation feedback (somatosensory feedback) will not only affect force production at local digits, but also at non-local digits as well. Derived from the maximal force ability at I, M, IM, and L digit conditions the current study shows removal of tactile sensation feedback will reduce the maximal force ability during individual digit tasks of the local digits, and possibly non-local digits as well. This is detrimental to functional use of the hand for gripping and tasks that require a high level of force to be produced by the finger flexor muscle group, and can lead to dropping objects, being unable to carry the same weight as their premorbid levels, etc. However, during a task involving the whole hand (except the thumb) the maximal force ability was maintained when only a subset of the digits had absent tactile sensation feedback. Regardless of normal and absent tactile sensation feedback, the total MVC force was not evenly shared by the individual digits involved in the task. Overall, I produced more force than M during IM, R produced more force than L during RL, and I produced a similar force to M, which was greater than R, which produced yet even more force than L during IMRL task. The distribution of the total MVC force was maintained across the individual digits only when the tactile sensation feedback was uniformly absent (IM) or intact (RL). However, the distribution of this force sharing pattern was effected in certain cases by the removal of tactile sensation feedback, such as during the task when tactile sensation feedback of the task involving digits were not uniformly affected (i.e., MVC at IMRL condition). These results support our hypothesis that absent tactile sensation feedback will interrupt the force sharing pattern at both local and non-local fingers. With absent tactile sensation feedback the force sharing pattern at the non-local digits was interpreted. This is observed during the MVC task as the total force produced during the IMRL condition was not significantly different from the anesthesia versus control trials, however the distribution of the force was significantly different. The overall force output when using all four fingers was, therefore, re-distributed among the four fingers. This interaction may be due to a compensatory strategy when tactile sensation feedback is absent or unreliable in the motor system.

Even though participants produced similar maximal force at IMRL condition of MVC task, individual finger force was not similar; specifically R and L fingers were significant lower after anesthesia procedure compared to the control. This finding further confirms our hypothesis that absent tactile sensation feedback (somatosensory feedback) will not only affect force production at local digits, but also at non-local digits as well. However, this effect only occurs when the tactile sensation is not uniformly intact or absent. When the tactile sensation was uniformly intact, during the MVC at RL condition, and uniformly absent, during the MVC at IM condition, force sharing pattern across the individual digits was maintained.

During a whole hand task (except the thumb) the force sharing pattern is inconsistent when tactile sensation feedback is absent in the index and middle fingers. This finding suggests that non-local digits can adapt their force distribution to maintain their MVC consistent. The adaptation may be taking place at the mechanical level of the force production ability by the finger flexor muscle groups, or cortical remapping in the center nervous system. Further research could be done looking into how the central nervous system coordinates mutli-digit forces to adapt to perform specific manual tasks with and without absent tactile sensation feedback. This could be including whether there is difference in how the central nervous system controls coordinated multi-digit forces when tactile sensation feedback is uniformly versus non-uniformly absent or intact.

However, the MVC was interrupted by absent tactile sensation feedback in both non-local and local digits. Observed in the MVC at I, M, IM conditions the local digits produce less force than the control, whereas in the MVC at R,RL conditions the non-local digits produced the same force as the control. Also, during the MVC at L condition the non-local digit produced less force during the anesthesia compared to the control. Therefore, there is an interaction of the absent tactile sensation feedback on non-local digits.

Effect of Digital Anesthesia in hand Functional Control – Enslaving Effect

The enslaving force (effect) is a quantitative measure of mechanical coupling in the hand, which involves various factors. The factors effecting the enslaving force are motor units for multiple digits in the extrinsic wrist and finger flexor and extensor muscles, diverging commands from the central nervous system, and mechanical coupling of multiple fingers in the hand (with greater coupling in adjacent fingers).

When I and R were the master finger (the instructed finger involved in the Ramp task), the enslaving effect maintained consistent between control and anesthesia groups. However, M and L enslaves the other fingers when tactile sensation feedback is absent compared to the control. These findings indicate that, out of the four digits in this study, index is the most independent and L is least independent finger. Therefore, during a whole hand task (except the thumb) the enslaving effect is interrupted by absent tactile sensation feedback at both local and non-local digits.

Knowing that the absence of tactile sensation feedback decreases MVC at the local and non-local digits (I, M, IM, L), is a point of interest in the results of the current study because the

MVC at L was decreased even though there was intact tactile sensation feedback in that digit. Combining this information with the data from the enslaving matrix, being that L is the also the digit that most enslaves the other digits when acting as the master finger under digital anesthesia, leads to some assumptions about functional use of the hand when tactile sensation feedback is absent. An extension for further research could be into testing a patient with absent tactile sensation in a subset of the hand (such as carpal tunnel syndrome). Such participant could perform the task, focusing on using L (the fifth digit) during the task (making it the master finger and therefore enslaving the other fingers), and investigating whether the participant will have a better chance of holding on the object (creating a more coordinated force in the other fingers which originally had a decreased MVC due to the absent tactile sensation) than if the participant focuses on holding the object by using I (the index finger). However, as seen in the whole hand (except the thumb) isometric task the maximal total force was maintained, focusing on putting force evenly through the whole hand may be more beneficial for functional use.

Effect of Digital Anesthesia in Hand Functional Control – Force Performance Accuracy

The final task (step task) indicated that digital anesthesia, and therefore absence of tactile sensation feedback, did not affect the force accuracy during a force production task. This is observed as there is no discrepancy between the anesthesia and control groups in Step task. Participants were able to maintain the proper amount of force to complete the Step task with and without tactile sensation feedback. This may have occurred because an online visual feedback was available and provided to the subject during the tasks.

The human body has various types of sensory feedback, tactile, visual, proprioceptive, etc. In varying conditions the body can rely on one sensation more than the others, as in many cases with healthy individuals, depending on which one is more beneficial for performing the task at hand. In the current study, the participants were able to view a screen, providing them with an online visual feedback, regardless of their tactile sensation feedback. Therefore, the visual feedback may have been able to override the somatosensory feedback signals during the tasks, acting as the primary source guiding motor executions. This visual feedback could be responsible for the allowance of the error-correction and describe the participants' ability to maintain the proper force production without tactile sensation feedback.

The current study has led to further questions about hand coordination and how tactile sensation feedback plays a role in the functional use of the hand. Another extension for further research is to investigate what changes the addition of the thumb to the current task makes. When adding on the thumb, the force sharing pattern may change, the total force will change, the thumb may have a different response to the absent tactile sensation feedback compared to the other digits that would need to be investigated to fully understand the complex movements of the hand in a functional pattern.

Our findings correlate well with existing literature on the effects on tactile sensation feedback on multi-digit coordination and hand control. As previously described by Hermsdorfer et al. 1999; Johansson et al. 1999; Edin et al. 1992; Flanagan and Wing 1997, tactile sensation feedback is responsible for how the forces are distributed throughout the hand, and the current study shows the pattern in which the hand distributes forces is interrupted by absent tactile sensation feedback. We found this interruption in force sharing is at non-local digits only, but MVC was decreased at both local and non-local digits. This finding is agreement with a study be Aoki et al. recently (2007) which indicated that sensory information at one digit affects the force modulation at local and non-local digits. Zhang et al. (2011, 2012, 2013, 2014) showed sensory information from one digit is shared across other digits to attain and maintain task-specific performance stability in patients with CTS, and this finding is concurrent with the findings of the current study. The current showed inconsistency in the force sharing pattern between the control and anesthesia trial leading to the assumption that non-local digits can adapt their force distribution to maintain their MVC consistent.

Study Limitation

A possible source of error was that the participants were assumed to have complete absent tactile sensation feedback during the anesthesia trial. The anesthesia procedure was performed correctly, by the appropriate provider, but different participants may have a variety of interpretations of what completely numb means. A light touch sensation test was performed before beginning the anesthesia trail but the participant may not have been fully compliant with the guidelines for the experiment of the anesthesia procedure and allowing for complete absent tactile sensation feedback.

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