Master's Thesis of Sport Science

Interpersonal synergies
- effect of sensory feedback modalities on synergy indices of multi-finger actions during force and torque production-

August 2020

Graduate School of
Seoul National University
Department of Physical Education
Human Movement Science Major

Sungjun Lee

Interpersonal synergies
- effect of sensory feedback modalities on synergy indices of multi-finger actions during force and torque production-

Advisor Jaebum Park

Submitting a master's thesis of Sport Science

August 2020

Graduate School of
Seoul National University
Department of Physical Education
Human Movement Science Major

Sungjun Lee

Confirming the master's thesis written by Sungjun Lee

August 2020

Chair	Seonjun Kim	(Seal)
Vice Chair	Jooeun Ahn	(Seal)
Examiner	Jaebum Park	(Seal)

Abstract

Interpersonal synergies

- effect of sensory feedback modalities on synergy indices of multi-finger actions during force and torque production-

Lee sung jun
Department of Physical Education
Human Movement Science
The Graduate School
Seoul National University

Interpersonal interactions can be commonly found in every activities such as lifting a heavy object, shaking hands, or clinking glasses. In such actions, each person must coordinate individual actions with the other person to accomplish a common motor task. If each person cannot accurately perceive the changes in actions of the counterpart, the common motor tasks will not be stably performed. In this situation, sensory feedback is likely to play a large role in the way each individual interact with one another and objects they commonly control. However, it is still unclear how the effect of feedback modalities appear when motor tasks are simultaneously performed by two different persons who has independent motor system. Therefore, the present study aimed to compare the control strategies utilized when two persons conducted the motor task together (inter-person condition) with the ones utilized when only one-person performed the same task (one-person condition), depending on the different sensory feedback modalities. For this study, all subjects performed the main tasks pressing down the finger-force sensors, which attached on the two ends of a customized plate of lever, to reach the target value of total force while balancing the forces of left and right hands. The main tasks consisted of 12 experimental conditions: (1) 'person condition (one-person vs. inter-person)', (2) 'feedback condition (stable: visual feedback vs. unstable: visual & somatosensory feedback)', and (3) 'force condition (MVC 10% vs. 20% vs. 30%)' (See Methods.2.3.2). Results showed that, $RMSE_{Force}$ and $RMSE_{torque}$, which mean performance errors, were higher in inter-person condition than one-person condition (See Fig 4,5). It seemed that it was more difficult to maintain the total force of both hands to the target force while balancing the forces of left and right hands when performing the main task with another person. However, when visual and somatosensory feedback were provided together at MVC 30%, the amount of error reduction about net torque ($RMSE_{torque}$) was greater in inter-person condition than in one-person condition (See Fig 5). In addition, the increment of torque stabilizing synergy indices ($\triangle V_{Torque}^{UH}$) under the same condition was higher in inter-person condition than in one-person condition (See Fig 9). This result indicates that when two persons produced submaximal force together, additional somatosensory feedback of unstable condition increases the coordination between both hands and decreases errors about balancing left and right hands. Therefore, additional somatosensory feedback plays an important role to overcome the physical constraints between those two persons with independent motor systems.

Keyword : Interpersonal interaction, visual feedback, somatosensory feedback, RMSE, synergy indices, net torque

Student Number : 2018-21948

Table of Contents

List of Figures

Chapter 1. INTRODUCTION

Interpersonal interactions can be commonly found in every activities such as lifting a heavy object, shaking hands, or clinking glasses. In such actions, each person must coordinate individual actions with the other person to stabilize a common mechanical outcome such as force, torque (Burstedt et al., 1997, Bosga and Meulenbroek, 2007). In the previous studies, quantitative method based on the framework of the uncontrolled manifold (UCM) hypothesis was used to identify the coordinated pattern of two person actions for stabilizing performance variable (e.g., force, torque) when the motor task was conducted with another person (Solnik et al., 2015, Slomka et al., 2015, Passos et al., 2018)

According to UCM hypothesis, inter-trial variance of the motor elements (e.g., muscles, joints and fingers) performed the tasks are quantified in two subspace. Variance in the UCM subspace (V_{UCM}) means that the each element interacted to keep the performance variable to a constant value. On the other hand, variance of the subspace orthogonal to the UCM (V_{ORT}) means that leads to changes in that performance variable. When if V_{UCM} is greater than V_{ORT}, then in terms of analysis, it is concluded that each motor element interacted to stabilizing the performance variable (Latash et al., 2002, Latash et al., 2007). Through this approach, the motor coordination for stabilizing performance variable between motor elements of two persons is defined as 'interpersonal synergy' in the motor control literature (Solnik et al., 2016, Passos et al., 2020).

Most studies of motor coordination between two persons who has independent motor system have emphasized the importance of sensory feedback modalities shared each other (Fine et al., 2013, Stoffregen et al., 2009, van der Wel et al., 2011). It means that each person cannot perfectly perceive the changes in mechanical variables produced by counterpart, so it is difficult to stably performed the motor task with another person. In this situation, sensory feedback is likely to play a large role in the way each individual interact with one another and objects they commonly control. According to previous studies, when performing the motor task with another person coupled by visual feedback, they are able to organize synergistic actions, which compensate errors each other (Romero et al., 2015, Solnik et al., 2015). In other previous studies, when somatosensory feedback which can cause mechanical contact associated sensory information was provided, each individual could stabilize the coordination of spontaneous movements between two persons (Sofianidis et al., 2012, Eils et al., 2017). These results indicate that visual and somatosensory feedback play an important role to overcome the physical constraints between independent motor systems.

Until recently, however, few studies have identified the effect of sensory feedback modalities on the interpersonal control strategies. Therefore, the present study aimed to compare the control strategies utilized when two persons conducted the motor task together (inter-person condition) with the ones utilized when only one-person performed the same task (one-person condition), depending on the different sensory feedback modalities. The motor task in the current study required all subjects to produce bimanual-finger force to reach the target force while maintaining 'zero' net torque between both hands using a customized lever. When performing the motor task, two types of feedback conditions were provided depending on the state of the lever being fixed or not (stable or unstable condition). Under the stable condition, the lever was fixed so that subjects could only receive visual feedback about the measured finger forces and computed net torque on the monitor. In contrast, under the unstable condition, the lever was unfixed so that subjects would be given the additional somatosensory feedback about the motion of lever resulting from changes in the force of the left and right hands.

Based on the mentioned studies that shows the importance of sensory feedback shared each other when performing the main task with another person, we set up two hypotheses as follow. The amount of performance error (RMSE) reduction would be greater in inter-person condition than one-person condition when visual and somatosensory feedback were provided simultaneously compared to when visual feedback was provided only (Hypothesis 1). In addition, if multiple sensory feedback was provided, the synergy indices would increase significantly in inter-person condition compared to in one-person condition (Hypothesis 2).

Chapter 2. METHODS

2.1. Subjects

A total of 18 right-handed male adults (27.4 ± 4.22 *years in age,* 174.1 ± 5.34 *cm in height,* 74.0 ± 8.99 *kg in body weight*) were recruited for this study. All subjects were free from any symptoms or disorders in neuromuscular function that would interfere with manual tasks. Prior to the experiment, each subject was requested to sign a consent form according to the procedure approved by Seoul National University Institutional Review Board (IRB No. 1907/003-015).

2.2. Apparatus

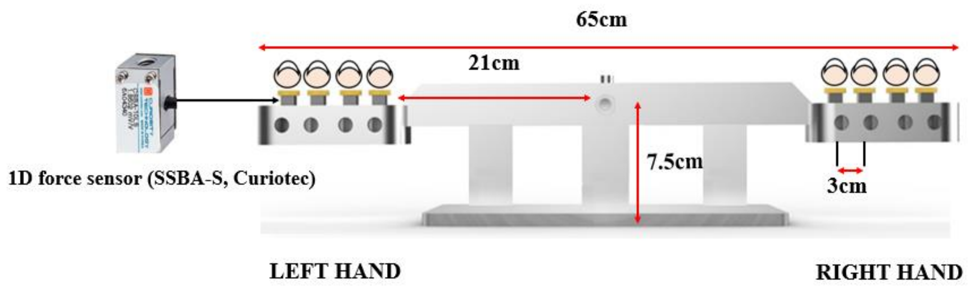


Figure 1. Apparatus for the bimanual force & torque production tasks. The stable condition defined in the present study means that the lever was fixed so that it could balance while subjects were pressing the sensors. On the other hand, the unstable condition means that the lever is not fixed. Thus it could be wobbled as the forces change of both hands.

Eight one-component force sensors (SSBA-S, *Curiotec Co.Ltd. Korea*) were used to measure normal forces generated at the fingertips except for the thumbs. The surface of each sensor was covered with 200-grit sandpaper to prevent from slipping between fingertips and the sensors. The force sensors were attached on the two ends of aluminum plate of lever (length 0.65m, width 0.06m). At each side of the lever, the sensors were placed at intervals of 0.03m to computed net torque between both hands (see Fig. 1). The heights of the force sensors and the lever axis (0.075m) were positioned equal to minimize the torque caused by the shear forces of fingers when measuring the pressing forces of eight fingers. In order to minimize friction between the axis and the lever plate, the axis of lever was made of ‘Teflon’. Finger force data were digitized at 200Hz sampling rate via an analog-to-digital converter using a customized Labview program (National Instrument, Austin, TX, USA). Real-time force and computed torque data were displayed on computer screen (24 inch diagonal, 1920 x 1080 pixels) placed 0.6 m away from each subject.

2.3. Measurements

2.3.1 Maximal voluntary contraction (MVC) task

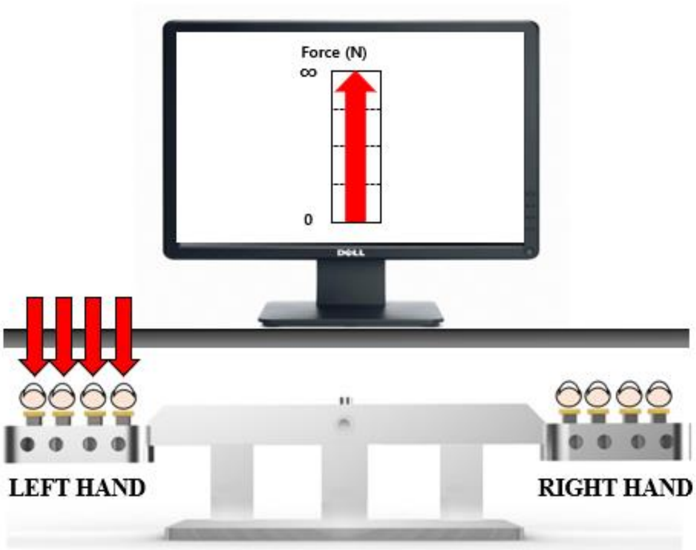


Figure 2. Maximum voluntary contraction (MVC) task. Subjects were required to produce maximum force for three seconds with the four fingers while the lever was fixed (Stable condition). MVC was measured twice for the right and left hand, respectively.

Before performing the main task, all subjects were required to simultaneously press the force sensors with the four fingers (except for the thumbs) of each hand as hard as possible for 3-s (Fig. 2). The maximal voluntary contraction force was measured twice for the right and left hands, respectively. After the MVC data of each hand were collected, the average MVC values across the two trials were used to set target force levels (MVC 10%, 20%, 30%) of the main task for each individual. To minimize the effect of fatigue during the MVC trials, 30-s break was given between the trials.

2.3.2 Bimanual force & torque production tasks

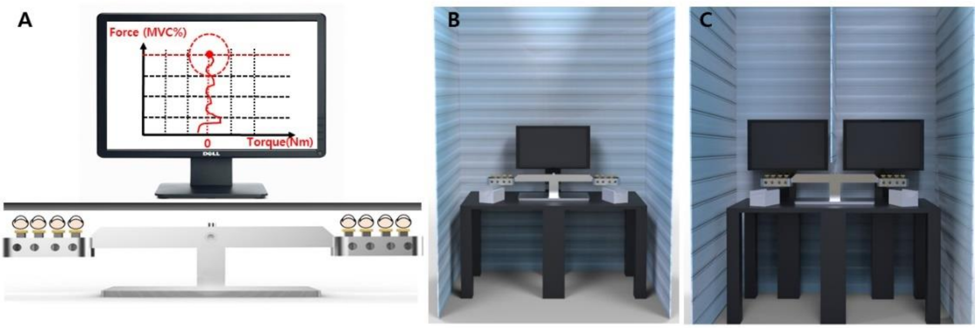


Figure 3. Schematic representation of the bimanual force & torque production tasks (a). The computer screen showed target force value (x-axis) and ‘zero’ net torque between both hands (y-axis). If the force values generated by the right and left hands are equal to each other, the red cursor will move vertically on the computer screen. the experimental setup for the one-person (b) and inter-person conditions (c). During the inter-person condition, partition was set up to exclude any physical interactions between the two persons sitting next to each other. In addition, no conversation was allowed between the subjects in order to eliminate effect of other types of feedback besides the defined feedback in the present study.

After subjects sat in front of the computer assigned, they were instructed to press down the sensors to set the sum of bimanual-finger force to reach the target force with ‘zero’ net torque between left and right hands (see Fig. 3-A). During the 10-s given to perform the main task, subjects were required to reach the target force as quickly as possible. For the main task completion, 10-s were given because it was considered that the duration of 10-s would not make subjects suffer from fatigue (Reschechtko et al., 2015, Christensen, 2017). When subjects produced the bimanual-finger force, the forearm was held stationary with Velcro straps to restricted forearm and wrist movement. In addition, a custom-fitted plastic block was placed underneath each subject's palms in order to ensure a constant configuration of the hand with respect to the sensors. Prior to beginning the measurements, all subjects practiced for 10 min to familiarize themselves with the main task.

There were a total of 12 experimental conditions, which were combinations of difference (1) 'person (one vs. inter-person)', (2) 'feedback (stable vs. unstable)', and (3) 'force level (MVC 10% vs. 20% vs. 30%)' factors. Two conditions consisted of the 'person' factor: one-person condition in which the main task was conducted alone using both hands; inter-person condition in which the same task was performed by randomly assigned two persons with one's left (right) hand and another's right (left) hand. When performing the main task of inter-person condition, partition was set up to exclude any physical interactions between the two persons participating in the same task together (See Fig. 3-B,C).

Two types of conditions were provided in 'feedback' factor, stable or unstable condition. Under stable condition, the lever was fixed so that it could balance while subjects were pressing the force sensors located on both sides of the lever plate. When performing the task in this state, all subjects were provided with the computed torque as a visual feedback because they could not directly sensed the torque between both hands through the movement of the lever. In contrast, under unstable condition, the lever was leaned to one side when the forces of each hand were not equal. Thus, unstable condition was regarded as subjects would be given the additional somatosensory feedback that directly sensed the movement of lever resulting from changes in the force of the left and right hands. In order to eliminate the learning effect between subjects, the order in which stable and unstable conditions were presented was randomized across subjects.

As the final factor, there were three conditions in the force level. According to each individual's measured MVC from each hand prior to the main task, subjects were required to reach the target force of 10%, 20%, and 30% MVC. Every subject repeatedly conducted the main task in each experimental condition for 20 trials with

10-s break between the trials. Thus, all subjects performed a total of 120 trials (2 conditions of feedback factor × 3 conditions of force factor × 20 trials = 120 trials) during one-person condition. In the inter-person condition, on the other hand, two persons performed the main task together using only left or right hand, so they switched hands and performed the same task again. Therefore, each subject performed a total of 240 trials (2 conditions of feedback factor × 3 conditions of force factor × 2 conditions of hand factor × 20 trials = 240 trials) during inter-person condition. In order to rule out the effect of fatigue from a lot of trials, 10 minutes break was given when changing the experimental conditions. Also, one-person and inter-person conditions were performed in different two days.

2.4. Data processing

Prior to the variable computation, the initial 4-s of total 10-s data were sorted out. Only later 6-s data were used in the analysis because it was considered that subjects stably maintained target force and 'zero' net torque using both hands during that period (Ferrand and Jaric, 2006, Koh et al., 2015). Classified force data were digitally low-pass filtered with a zero-lag, fourth-order Butterworth filter at 10Hz using customized MATLAB (MathWorks Inc., MA, USA) codes (Solnik et al., 2015, Park et al., 2012). For the one-person condition, total force of both hands (F_{TOT}) was defined as the sum of forces produced by the Index, Middle, Ring, and Little fingers of both hands. Likewise, for the inter-person condition, F_{TOT} was determined as forces produced by one subject's four fingers of left (right) hand and another's four fingers of right (left) hand. The following two variables were computed from F_{TOT}, to test the hypotheses in the present study: (1) root-mean-squared error (RMSE) as a performance variable, (2) synergy indices as coordination variables.

2.4.1 Root-mean-squared error (RMSE)

In the present study, root-mean-squared error (RMSE) was defined as performance variable. The RMSE was computed by classifying the errors about force ($RMSE_{Force}$) and torque($RMSE_{Torque}$), respectively. $RMSE_{Force}$ was calculated by the deviation of each subject's F_{TOT} from the target force (MVC 10%, 20%, and 30%). A high values of $RMSE_{Force}$ means that the accuracy of the total force output was reduced. $RMSE_{Torque}$ was calculated by the deviation of the computed torque (measured bimanual finger force × moment arm) from 'zero' net torque between both hands. The large $RMSE_{Torque}$ indicates that the multi-finger forces between left and right hands were less balanced during the task. RMSE was computed by the following equation. 1-1, 1-2.

$$\boldsymbol{RMSE_{force}} = \sqrt{\frac{\sum_{i=1}^{n}(F_{target}-F_i)^2}{n}} \times \frac{1}{F_{target}} \quad \text{(Equation. 1-1)}$$

,where, F_{target} represents each subject's target force according to 10%, 20%, and 30% MVC. F_i was sum of the forces produced by Index, Middle, Ring, and Little fingers of both hands at each trial. n means the total number of 20 trials in each force level (10%, 20%, and 30%). The error value was normalized by F_{target} to reflect the differences in MVC between subjects.

$$\boldsymbol{RMSE_{torque}} = \sqrt{\frac{\sum_{i=1}^{n}(T_{zero}-T_i)^2}{n}} \quad \text{(Equation. 1-2)}$$

,where, T_{zero} represents 'zero' net torque achieved when four-finger forces of left hands and those of right hand are equal. T_i was torque at each trial computed by the multiplication of measured force and moment arm between the axis of the lever and each force sensor. *n* means the total number of 20 trials in each force level (10%, 20%, and 30%).

2.4.2 Hierarchical analysis of multi-finger synergy indices

Synergy indices, which were defined as coordination variables, were computed using the framework of uncontrolled manifold (UCM) analysis. The UCM analysis assumes that a controller (CNS) with redundant motor system acts in a space of elemental variables. At this time, controller selects subspace (UCM) within the state space of the elements (fingers) to keep stable the desired value of the performance variable (e.g., force, torque). Therefore, UCM variance (V_{UCM}) means that the each component interacted to keep the performance variable to a stable value. On the other hand, V_{ORT}, which is the orthogonal variance of the V_{UCM}, means that leads to changes in that performance variable. When if V_{UCM} is greater than V_{ORT}, then in terms of analysis, it is concluded that each motor element interacted to stabilizing the performance variable (Latash et al., 2002, Scholz et al., 2003). In current study, synergy indices were systematically analyzed at two different hierarchies to confirm how the redundant motor system was organized (Upper level of hierarchy (UH) : coordination between both hands, Lower level of hierarchy (LH) : coordination of four fingers within each hand). The hierarchy analysis of synergy indices were calculated using the equation below.

The sum of the changes in each elemental variables (△EV) cause changes in the performance variable (△PV). The elemental variables in the current analysis mean finger force vector, and the performance variables are total finger forces (F_{TOT}) and total moment of finger forces (T_{TOT}).

$$\Delta PV = J \cdot \Delta EV \qquad \text{(Equation. 2-1)}$$

'J' stands for 1 by n Jacobian matrix. Here 'n' is the number of degrees of freedom of the elemental variables in the task. When computing the upper level of hierarchy, 1 by 8 Jacobian matrix ([1,1,1,1,1,1,1,1]) is substituted. For calculating lower level of hierarchy, 1 by 4 Jacobian matrix ([1,1,1,1]) is applied. If PV is M_{TOT}, then the Jacobian matrix is substituted the moment arm from the lever axis (UH: [point of application of left hand, point of application of right hand] , LH-left hand: [-0.3m, -0.27m, -0.24m, -0.21m], LH-right hand: [0.21m, 0.24m, 0.27m, 0.3m]). The UCM is defined as a unit vector (e_i) in the space of elemental variable that does not any change the certain performance variables (PV).

$$0 = J \cdot e_i \qquad \text{(Equation. 2-2)}$$

Then, compute the null space of the Jacobian and the demeaned data of elemental variables are projected onto the null space. At this time, the component of parallel to the UCM space is calculated by the equation.2-3.

$$f_{\parallel} = \sum_i^{n-p} (e_i{}^T \cdot df) \cdot e_i \qquad \text{(Equation. 2-3)}$$

($f_{/\!/}$ = components of force parallel to UCM space, p = number of DOFs of the performance variable, df = changes of total finger forces, e_i = unit vector defining the UCM space)

The component of orthogonal to the UCM space is computed by the equation.2-4.

$$f_{\perp} = df - f_{\parallel} \qquad \text{(Equation. 2-4)}$$

Calculate the amount of variance per degree of freedom parallel to the UCM using the equation.2-5. This component of parallel variability does not lead to changes of the performance variable (e.g., a constant F_{TOT} or a constant M_{TOT}).

$$V_{UCM} = \frac{\Sigma |f_{\parallel}|^2}{(n-p)\cdot N_{trials}} \qquad \text{(Equation. 2-5)}$$

Then, compute the amount of variance per degree of freedom orthogonal to the UCM using the equation.2-6. This component of perpendicular variability resulted in the change performance variable such as a constant F_{TOT} or a constant M_{TOT}. that is, the V_{ORT} responsible for the errors for performance variable.

$$V_{ORT} = \frac{\Sigma |f_{\perp}|^2}{p\cdot N_{trials}} \qquad \text{(Equation. 2-6)}$$

The synergy indices (ΔV) were computed by the following equation.2-7. First, an index was calculated by dividing the V_{UCM} by the degrees of freedom of the corresponding subspace, subtracting V_{ORT} from it. Then the index was normalized by the total variance (V_{TOT}) per degree of freedom.

$$\Delta V = \frac{V_{UCM}/DOF_{UCM} - V_{ORT}/DOF_{ORT}}{V_{TOT}/DOF_{TOT}} \qquad \text{(Equation. 2-7)}$$

2.5. Statistical analysis

All data were expressed as mean ± standard error (SE). Statistical analysis was conducted using SPSS 21.0. Three-way repeated measures ANOVA ([*Person: One-person vs. Inter-person*]×[*Feedback: Stable vs. Unstable*]×[*Force level: MVC 10% vs. 20% vs. 30%*]) were performed for all variables (RMSE, Synergy indices). One-way repeated measures ANOVA or paired t-test was used as a post hoc in the analysis of interactions effect. Mauchly's sphericity test was conducted to confirm the assumptions of sphericity. If the sphericity assumption was violated, Greenhouse-Geisser correction was used as an alternative. Pair-wise comparisons with Bonferroni correction were performed where appropriate. Statistical significance was set at $P < 0.05$.

Chapter 3. RESULTS

3.1. Performance variables

3.1.1 RMSE$_{Force}$

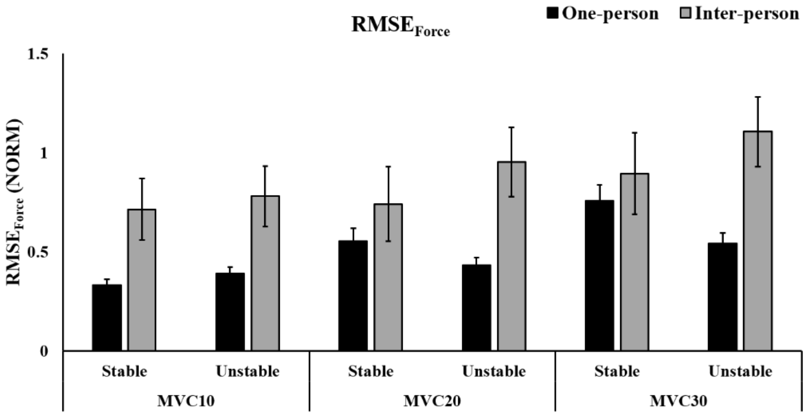


Figure 4. Average error values (RMSE$_{Force}$) about the each target force (MVC 10%, 20%, 30%) for the one-person condition (black bar) and inter-person condition (gray bar) during bimanual force & torque production tasks. Stable and unstable conditions refer to different feedback modalities when performing the task (stable: visual feedback, unstable: visual & somatosensory feedback). Average RMSE$_{Force}$ for one-person and inter-person conditions are presented with bars representing standard error (SE).

Fig4. illustrates errors between the total finger force of both hands ($\boldsymbol{F_{TOT}}$) and the target force ($\boldsymbol{F_{target}}$) in each condition. The results of **RMSE$_{Force}$** showed significant main effects of person ($F_{[1,17]}$ = 5.27, p = 0.035, ηp^2 = 0.24), and force ($F_{[1.33,2.65]}$ = 20.19, p < 0.001, ηp^2 = 0.54). There also was a significant person * feedback two-way interaction ($F_{[1,17]}$ = 9.50, p = 0.007, ηp^2 = 0.36) and three-way interaction in **RMSE$_{Force}$** ($F_{[2,34]}$ = 7.83, p = 0.002, ηp^2 = 0.32). Significant interaction between person and feedback factors were found at MVC 20% ($F_{[1,17]}$ = 8.18, p = 0.011, ηp^2 = 0.33) and MVC 30% ($F_{[1,17]}$ = 17.38, p = 0.001 , ηp^2 = 0.51) but not at MVC 10%. At MVC 20%, the **RMSE$_{Force}$** of inter-person condition was significantly greater than one-person condition when performing the main task under unstable condition only (p = 0.005). Especially at MVC 30%, **RMSE$_{Force}$** of one-person condition decreased in unstable condition (p = 0.002), whereas the error value of inter-person condition increased ($p = 0.05$). Accordingly, **RMSE$_{Force}$** of inter-person condition at MVC 30% was larger than that of one-person condition as at MVC 20%, under unstable condition ($p = 0.004$).

3.1.2 RMSE$_{Torque}$

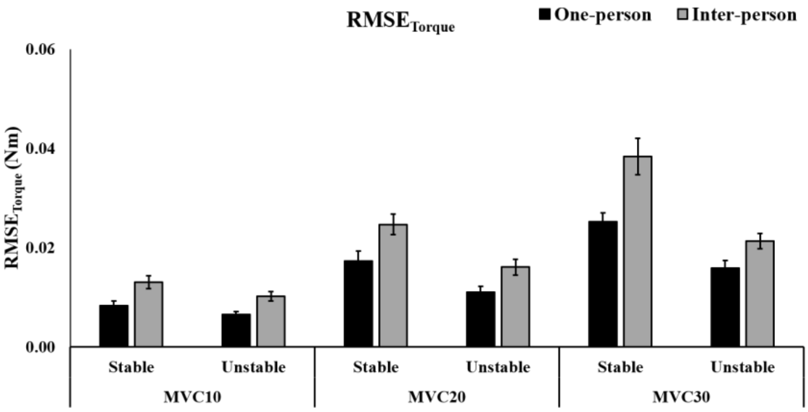


Figure 5. RMSE$_{Torque}$ means average error values for 'zero' net torque between both hands during bimanual force & torque production tasks. The large RMSE$_{Torque}$ indicates that multi-finger forces between left and right hands were less balanced during the task. Averaged across-subjects RMSE$_{Torque}$ with standard error bars are shown for the one-person (black bar) and inter-person (gray bar) conditions.

The **RMSE$_{Torque}$** means the deviation of the computed torque between both hands from 'zero' net torque (***T_{zero}***). The results of **RMSE$_{Torque}$** for person, feedback and force condition are presented in Fig .5. There was significant main effects of person ($F_{[1,17]} = 29.12$, $p < 0.001$, $\eta p^2 = 0.63$), feedback ($F_{[1,17]} = 26.98$, $p < 0.001$, $\eta p^2 = 0.61$) and force ($F_{[1.42,24.09]} = 107.75$, $p < 0.001$, $\eta p^2 = 0.86$). **RMSE$_{Torque}$** showed person * feedback two-way interaction ($F_{[1,17]} = 5.20$, $p = 0.036$, $\eta p^2 = 0.23$), reflecting that reduction in **RMSE$_{Torque}$** observed under unstable condition is more pronounced when the main task was conducted with another person than when the main task was performed alone. Post hoc analysis revealed that when performing the main task under unstable condition, **RMSE$_{Torque}$** was reduced in both one-person ($p < 0.001$) and inter-person conditions ($p < 0.001$). The difference between the stable and unstable condition increased when two persons conducted the main task together (p = 0.036) (Fig.5).

3.2. Coordination variables

3.2.1. Force stabilizing synergy of upper hierarchy ($\triangle V_{Force}^{UH}$)

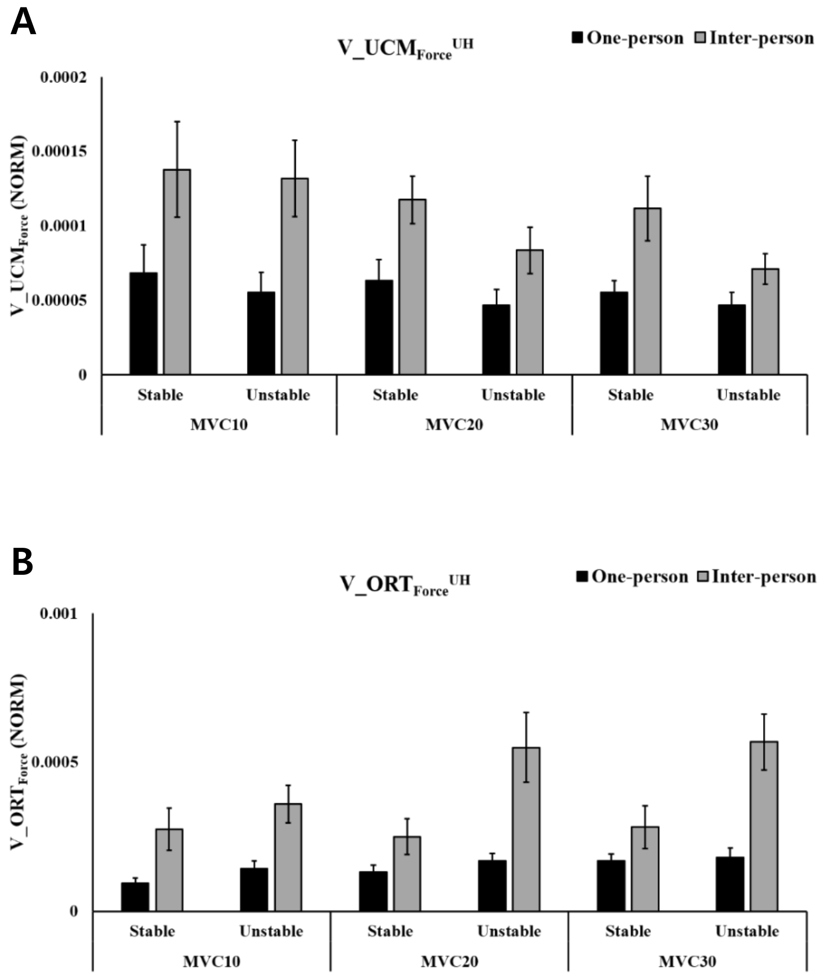


Figure 6. Results of the two components of variance on the uncontrolled manifold analysis. (a) Intertrial variance along the UCM ($V\_UCM_{Force}^{UH}$) and (b) variance orthogonal to the UCM ($V\_ORT_{Force}^{UH}$) were computed with respect to the total forces of both hands. Averaged across-subjects values with standard error bars are shown for the one-person condition (black bar) and inter-person conditions (gray bar). Note the difference scales of the Y-axes in the panels chosen to optimize visual perception of the results.

To quantify synergy indices of upper hierarchy that stabilized $\boldsymbol{F_{TOT}}$, we analyzed the structure of inter-trial variance in total forces generated by both hands. The results present the relative magnitude between $VUCM_{Force}^{UH}$ and $VORT_{Force}^{UH}$ (See p.10 for synergy index computation)of upper hierarchy in each condition (Fig.6-A,B). Overall, $VUCM_{Force}^{UH}$ of inter-person condition was greater than that of one-person condition. As the MVC% increased, magnitude of $VUCM_{Force}^{UH}$ decreased. These findings were supported by three-way repeated measures ANOVAs on $VUCM_{Force}^{UH}$ with factors of person (two levels: one-person and inter-person), feedback (two levels: visual and visual & somatosensory) and force (three levels: MVC 10%, MVC 20% and MVC 30%). The results showed significant main effects of person ($F_{[1,17]} = 15.14$, $p = 0.001$, $\eta p^2 = 0.47$) and force ($F_{[1.22,20.70]} = 5.22$, $p < 0.027$, $\eta p^2 = 0.24$) (Fig.6-A). $VORT_{Force}^{UH}$ showed significant main effects of person ($F_{[1,17]} = 22.27$, $p < 0.001$, $\eta p^2 = 0.57$) , feedback ($F_{[1,17]} = 6.69$, $p = 0.019$, $\eta p^2 = 0.28$) and force ($F_{[2,34]} = 3.68$, $p = 0.036$, $\eta p^2 = 0.18$). Significant person × feedback two-way interaction was found in $VORT_{Force}^{UH}$ ($F_{[1,17]} = 4.98$, $p = 0.039$, $\eta p^2 = 0.23$). Post hoc analysis showed that $VORT_{Force}^{UH}$ significantly increased when performing the motor task with another person under unstable condition compared to stable condition, whereas such difference was not present in one-person condition ($p = 0.024$) (Fig.6-B).

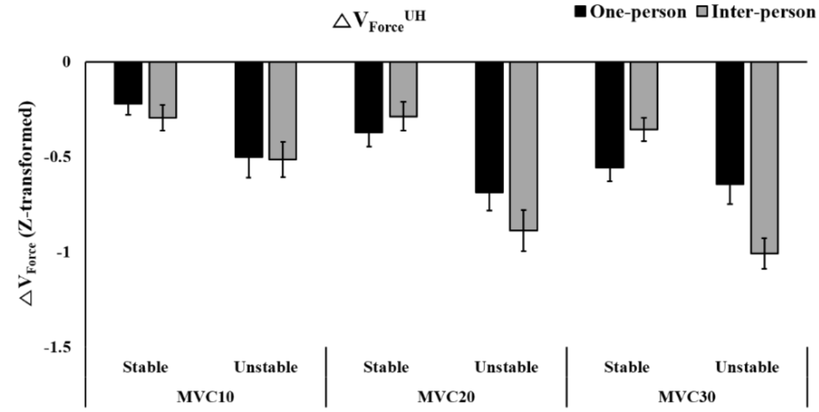


Figure 7. Force stabilizing synergy indices between both hands ($\triangle V_{Force}^{UH}$) computed as the difference between $V\_UCM_{Force}^{UH}$ and $V\_ORT_{Force}^{UH}$. The index was normalized by the MVC for each subject and averaged over 6-s of the force data. $\triangle V_{Force}^{UH}$ averaged across subjects with standard error bars for the one-person condition (black bar) and inter-person conditions (gray bar).

Fig. 7 illustrates the force stabilizing synergy indices ($\triangle V_{Force}^{UH}$) of upper hierarchy in each condition. In general, the values of $\triangle V_{Force}^{UH}$ was negative, meaning that the variance of $V\_UCM_{Force}^{UH}$ was smaller than $V\_ORT_{Force}^{UH}$. This shows that the combination of forces between left and right hands were formed as a positive covariation. According to three-way repeated measures ANOVAs, significant main effects of feedback ($F_{[1,17]} = 57.42$, $p < 0.001$, $\eta p^2 = 0.77$) and force ($F_{[2,34]} = 24.32$, $p < 0.001$, $\eta p^2 = 0.59$) as well as significant person * feedback two-way interaction was found in $\triangle V_{Force}^{UH}$ ($F_{[1,17]} = 4.52$, $p = 0.048$, $\eta p^2 = 0.21$). There also was significant three-way interaction of person, feedback and force factors appeared in $\triangle V_{Force}^{UH}$ ($F_{[2,34]} = 6.39$, $p = 0.004$, $\eta p^2 = 0.27$). Post hoc analysis confirmed that there were no significant person × feedback interactions in $\triangle V_{Force}^{UH}$ at MVC 10% and 20%. However, there was significant interaction of the two factors (person × feedback) at MVC 30% ($p = 0.001$). $\triangle V_{Force}^{UH}$ significantly decreased when performing the motor task with another person under unstable condition, whereas such difference was not present in one-person condition.

3.2.2. Torque stabilizing synergy of upper hierarchy ($\triangle V_{Torque}^{UH}$)

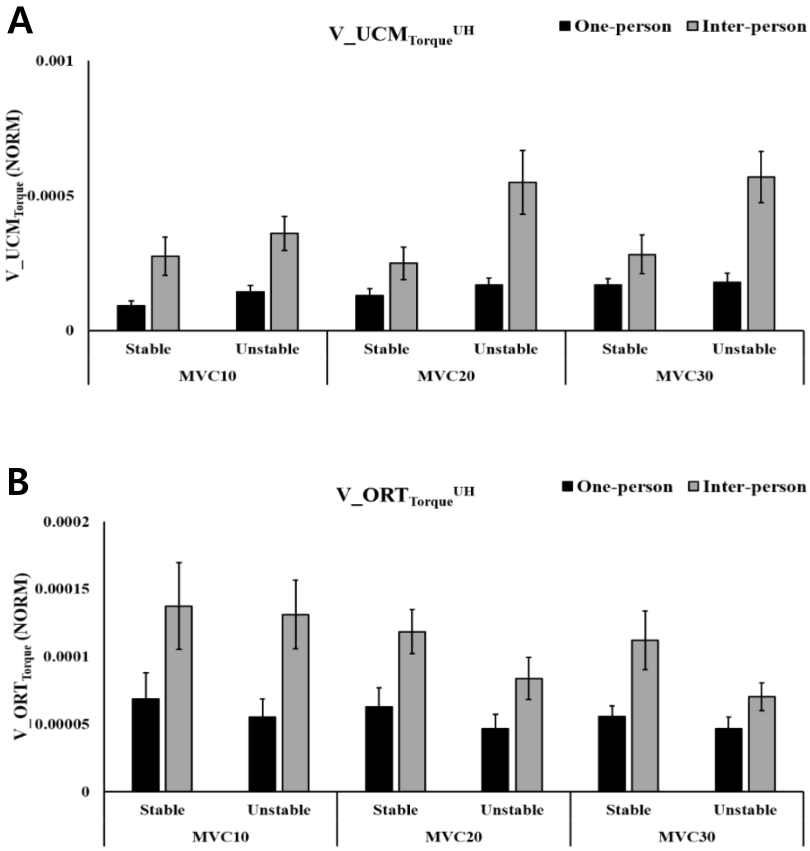


Figure 8. Two components of intertrial variance (a) V_UCM$_{Torque}^{UH}$, (b) V_ORT$_{Torque}^{UH}$ were computed with respect to the net torque (T_{zero}) between both hands using the UCM analysis. The values of V_UCM$_{Torque}^{UH}$ and V_ORT$_{Torque}^{UH}$ averaged across subjects with standard error bars for the one-person condition (black bar) and inter-person conditions (gray bar). Note the difference scales of the Y-axes in the panels chosen to optimize visual perception of the results.

To quantify torque stabilizing synergy indices of between left hand right hands, we analyzed the relative magnitude between V_UCM$_{Torque}^{UH}$ and V_ORT$_{Torque}^{UH}$ (See p.10 for synergy indices computation). The difference in V_UCM$_{Torque}^{UH}$ and V_ORT$_{Torque}^{UH}$ according to each person, feedback, force condition are summarized in Fig.8. V_UCM$_{Torque}^{UH}$ showed significant main effects of person ($F_{[1,17]}$ = 22.13, p < 0.001, ηp^2 = 0.57), feedback ($F_{[1,17]}$ = 6.83, p = 0.018, ηp^2 = 0.29) and force ($F_{[2,34]}$ = 3.68, p = 0.036, ηp^2 = 0.18). There was significant person × feedback two-way interaction appeared in $V\_UCM_{Torque}^{UH}$ ($F_{[1,17]} = 5.04$, $p = 0.038$, $\eta p^2 = 0.30$). Post hoc analysis discovered that when performing the main task with another person, $V\_UCM_{Torque}^{UH}$ was significantly elevated in unstable condition compared to stable condition ($p = 0.023$). In one-person condition, however, there was no difference between feedback conditions (Fig. 8-A). Generally, $V\_ORT_{Torque}^{UH}$ of inter-person condition was greater than that of one-person condition (Fig. 8-B). As the MVC% was elevated, magnitude of $V\_ORT_{Torque}^{UH}$ declined. This observation was supported by statistical analysis. The three-way repeated measures ANOVAs on $V\_ORT_{Torque}^{UH}$ including the person, feedback and force factors revealed that the main effects of person and force factors were significant (person: $F_{[1,17]} = 15.02$, $p = 0.001$, $\eta p^2 = 0.47$; force: $F_{[1.26,21.35]} = 4.90$, $p = 0.031$, $\eta p^2 = 0.22$, respectively).

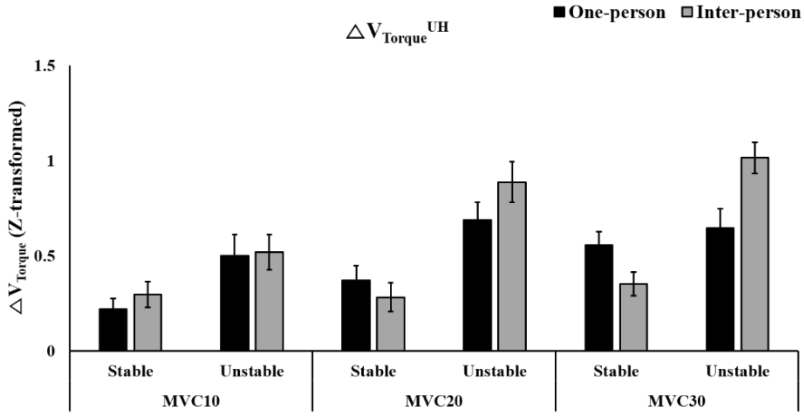
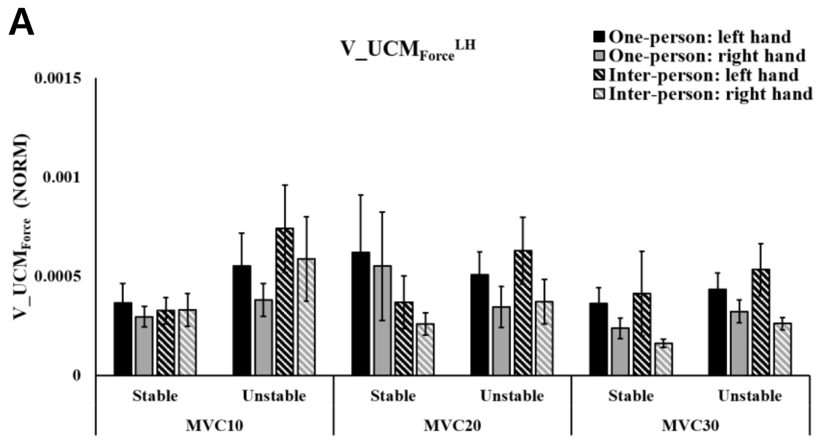


Figure 9. Torque stabilizing synergy indices between both hands ($\triangle V_{Torque}^{UH}$) computed as the difference between $V\_UCM_{Torque}^{UH}$ and $V\_ORT_{Torque}^{UH}$. The index was normalized by the MVC for each subject and averaged over 6-s of the force data. $\triangle V_{Torque}^{UH}$ averaged across subjects with standard error bars for the one-person condition (black bar) and inter-person conditions (gray bar).

The results of torque stabilizing synergy indices ($\triangle V_{Torque}^{UH}$) showed significant main effects of feedback ($F_{[1,17]} = 59.73$, $p < 0.001$, $\eta p^2 = 0.78$), force ($F_{[2,34]} = 24.33$, $p < 0.001$, $\eta p^2 = 0.59$) and significant person * feedback two-way interaction ($F_{[1,17]} = 4.62$, $p = 0.046$, $\eta p^2 = 0.21$). Further, significant three-way interaction of person, feedback and force factors appeared in $\triangle V_{Torque}^{UH}$ ($F_{[2,34]} = 6.56$, $p = 0.004$, $\eta p^2 = 0.28$). Post hoc analysis confirmed that $\triangle V_{Torque}^{UH}$ showed no significant two-way interaction of person and feedback factors at MVC 10% and 20%. However, there was significant person× feedback interaction at MVC 30% ($p = 0.001$). Especially at MVC 30%, when conducting the main task with another person, $\triangle V_{Torque}^{UH}$ in unstable condition increased compared to stable condition ($p < 0.001$), whereas one-person condition did not differ between feedback modalities. Accordingly, $\triangle V_{Torque}^{UH}$ of inter-person condition at MVC 30% was greater than that of one-person condition, under unstable condition ($p = 0.009$) (Fig. 9).

3.2.3 Force stabilizing synergy of lower hierarchy ($\triangle V_{Force}^{LH}$)



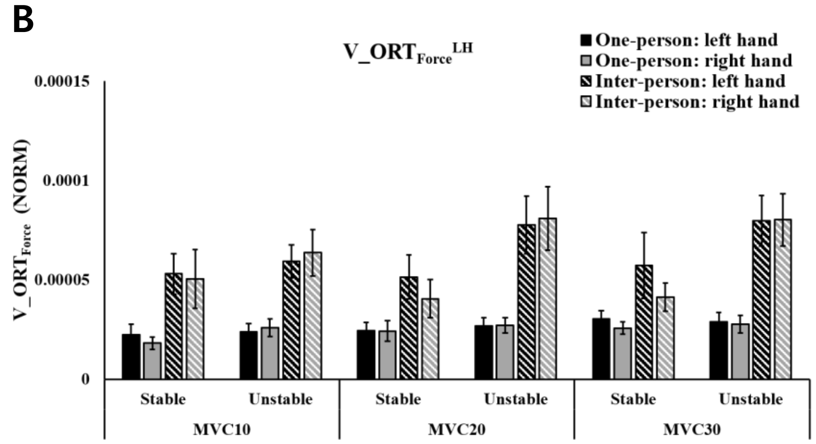


Figure 10. Two components of intertrial variance (a) $V\_UCM_{Force}^{LH}$, (b) $V\_ORT_{Force}^{LH}$ were computed with respect to the total forces of each hand. Averaged across-subjects values with standard error bars are shown for each hand of the person conditions: one-person-left hand (black colored bar), one-person-right hand (gray colored bar), inter-person-left hand (black striped bar) and inter-person-right hand (gray striped bar). Note the difference scales of the Y-axes in the panels chosen to optimize visual perception of the results.

We analyzed the structure of inter-trial variance in resultant forces produced by each hand to quantify force stabilizing synergy indices of lower hierarchy. The difference in $V\_UCM_{Force}^{LH}$ and $V\_ORT_{Force}^{LH}$ according to each person, feedback, force condition are summarized in Fig. 10. There was no significant interaction and main effects in $V\_UCM_{Force}^{LH}$ for both left and right hands (Fig. 10-A). In the left hand of $V\_ORT_{Force}^{LH}$, there was only significant main effect of person ($F_{[1,17]}$ = 25.79, $p < 0.001$, $\eta p^2 = 0.60$); in the right hand of $V\_ORT_{Force}^{LH}$, significant main effect of person ($F_{[1,17]} = 17.68$, $p = 0.001$, $\eta p^2 = 0.51$) and feedback ($F_{[1,17]} = 7.04$, $p = 0.017$, $\eta p^2 = 0.29$) with significant person × feedback two-way interaction ($F_{[1,17]} = 5.17$, $p = 0.036$, $\eta p^2 = 0.23$) appeared (Fig. 10-B) . Post hoc analysis showed that $V\_ORT_{Force}^{LH}$ of right hand significantly increased in case of performing the main task with another person under unstable condition ($p = 0.021$). On the other hand, there was no change on $V\_ORT_{Force}^{LH}$ by conducting the main task alone.

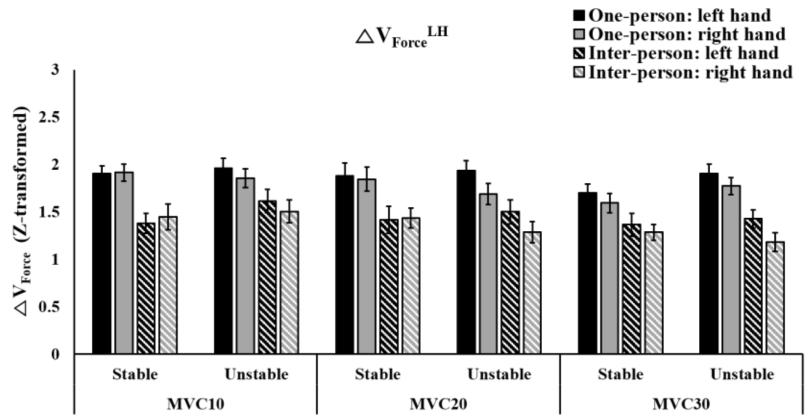
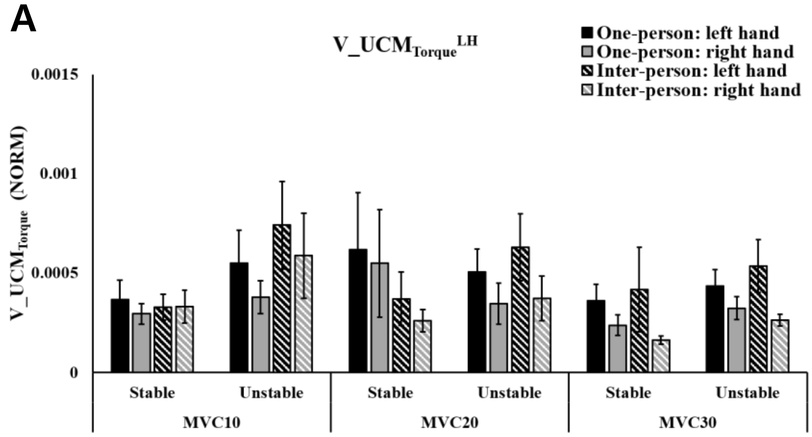


Figure 11. Force stabilizing synergy indices among the individual fingers of each hand ($\triangle V_{Force}^{LH}$) computed as the difference between $V\_UCM_{Force}^{LH}$ and $V\_ORT_{Force}^{LH}$. The index was normalized by the MVC for each subject and averaged over 6-s of the force data. $\triangle V_{Force}^{LH}$ averaged across subjects with standard error bars for each hand of the person conditions: one-person-left hand (black colored bar), one-person-right hand (gray colored bar), inter-person-left hand (black striped bar) and inter-person-right hand (gray striped bar).

The force stabilizing synergy indices ($\triangle V_{Force}^{LH}$) in each person, feedback, force condition were also analyzed in lower hierarchy and are presented in Fig. 11. For the left hand, the $\triangle V_{Force}^{LH}$ of one-person condition was higher than inter-person condition. This finding was supported by statistical analysis. There was only significant main effect of person on $\triangle V_{Force}^{LH}$ of left hand ($F_{[1,17]} = 53.24$, $p < 0.001$, $\eta p^2 = 0.76$). In case of the right hand, significant main effects of person and force appeared (person: $F_{[1,17]} = 14.41$, $p = 0.001$, $\eta p^2 = 0.46$; force: $F_{[2,34]} = 7.41$, $p = 0.002$, $\eta p^2 = 0.30$, respectively). As with the result of left hand, $\triangle V_{Force}^{LH}$ of one-person condition was greater than inter-person condition.

3.2.4 Torque stabilizing synergy of lower hierarchy ($\triangle V_{Torque}^{LH}$)

A



B

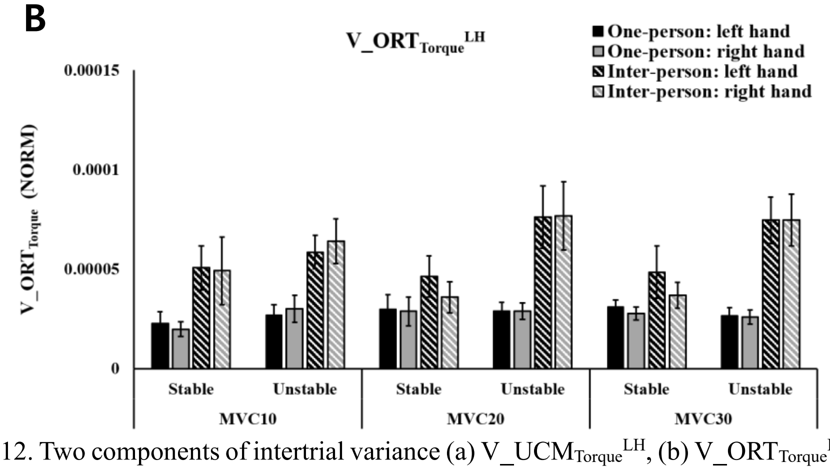


Figure 12. Two components of intertrial variance (a) $V\_UCM_{Torque}^{LH}$, (b) $V\_ORT_{Torque}^{LH}$ were computed with respect to the torque among the individual fingers of each hand. Averaged across-subjects values with standard error bars are shown for each hand of the person conditions: one-person-left hand (black colored bar), one-person-right hand (gray colored bar), inter-person-left hand (black striped bar) and inter-person-right hand (gray striped bar). Note the difference scales of the Y-axes in the panels chosen to optimize visual perception of the results.

The relative $V\_UCM_{Torque}^{LH}$ and $V\_ORT_{Torque}^{LH}$ (See p.10 for synergy indices computation) of lower hierarchy in each condition are presented in Fig.12. There were no significant interactions and main effects in $V\_UCM_{Torque}^{LH}$ for both left and right hands (Fig. 12-A). There was no significant interactions and main effects in $V\_ORT_{Torque}^{LH}$ for left hand. In the $V\_ORT_{Torque}^{LH}$ of right hand, significant main effects of person ($F_{[1,17]} = 12.14$, $p = 0.003$, $\eta p^2 = 0.42$) and feedback ($F_{[1,17]} = 6.71$, $p = 0.019$, $\eta p^2 = 0.28$) with significant person × feedback two-way interaction were found ($F_{[1,17]} = 5.53$, $p = 0.031$, $\eta p^2 = 0.25$) (Fig. 12-B). According to the post hoc analysis, in case of performing the main task with another person under unstable condition, $V\_ORT_{Torque}^{LH}$ of right hand quite increased ($p = 0.018$). However, no difference between feedback condition appeared in one-person condition.

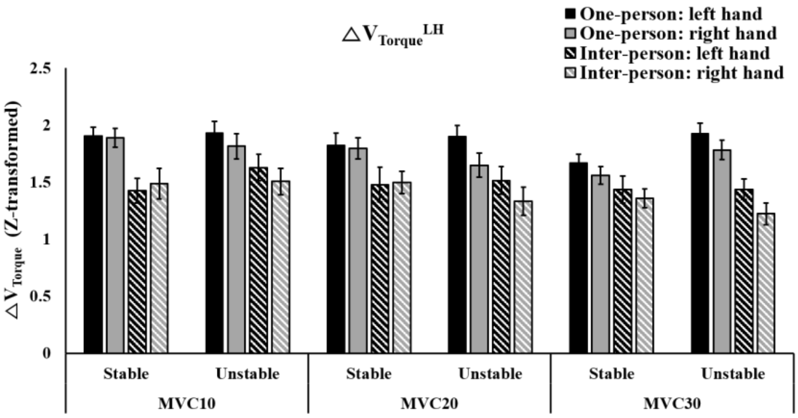


Figure 13. Torque stabilizing synergy indices among the individual fingers of each hand ($\triangle V_{Force}^{LH}$) computed as the difference between $V\_UCM_{Torque}^{LH}$ and $V\_ORT_{Torque}^{LH}$. The index was normalized by the MVC for each subject and averaged over 6-s of the force data. $\triangle V_{Torque}^{LH}$ averaged across subjects with standard error bars for each hand of the person conditions: one-person-left hand (black colored bar), one-person-right hand (gray colored bar), inter-person-left hand (black striped bar) and inter-person-right hand (gray striped bar).

The results showed the difference of the torque stabilizing synergy indices ($\triangle V_{Torque}^{LH}$) of lower hierarchy according to person, feedback and force condition (Fig. 13). In the left hand, significant main effect of person ($F_{[1,17]} = 7.54$, $p < 0.001$, $\eta p^2 = 0.64$) and person × feedback × force three-way interaction was found ($F_{[2,34]}$ =

4.09, p = 0.026, ηp^2 = 0.19). Post hoc analysis discovered that person × feedback interaction tended to be more pronounced in MVC 30% condition but the interaction was only marginally significant ($F_{[1,17]}$ = 3.88, p = 0.065, ηp^2 = 0.19). The three-way repeated measured ANOVAs on $\triangle V_{Torque}^{LH}$ of right hand showed that only significant main effects of person ($F_{[1,17]}$ = 10.83, p = 0.004, ηp^2 = 0.39) and force factors ($F_{[2,34]}$ = 5.44, p = 0.009, ηp^2 = 0.24). As with the $\triangle V_{Force}^{LH}$ of left hand, $\triangle V_{Torque}^{LH}$ of one-person condition was higher than inter-person condition

Chapter 4. DISCUSSION

4.1. One-person vs Inter-person

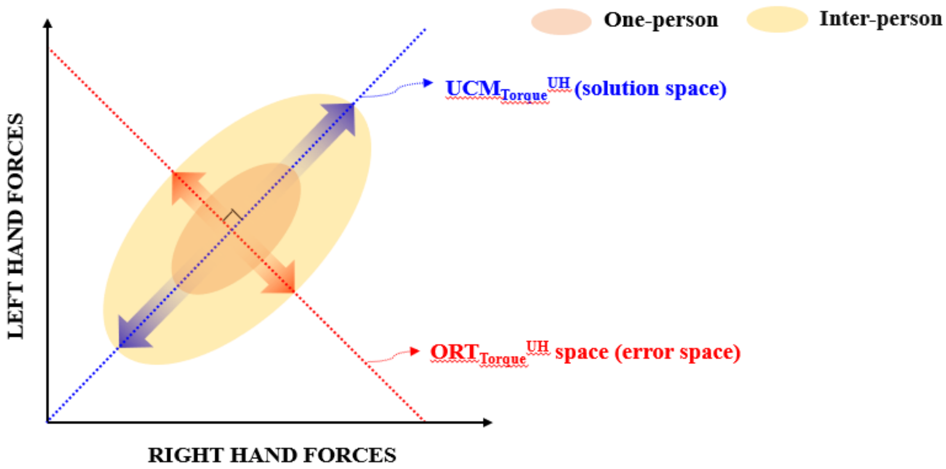


Figure 14. Schematic representation of difference in torque stabilizing synergy indices between person conditions.

Our results of RMSE showed that overall $RMSE_{Force}$ and $RMSE_{Torque}$ were greater in inter-person condition than one-person condition. In other words, compared to the one-person condition, it was more difficult to maintain the total force of both hands to the target force while balancing the forces of left and right hands in inter-person condition. The findings of current study could also associated with outcomes of previous studies. when the motor task was performed interacting with another person, the two persons could not control coordination of both hands as it was carried out alone. It was thus suggested that individuals should use a new feedback-based anticipatory control strategy to successfully perform the motor task with another person (Knoblich et al., 2003, Mason and MacKenzie, 2005). If error or noise arises in the other person (e.g., right hand of the subject), the dynamics of interpersonal aspects might be mutually influential (Kodama et al., 2015).

Our results of synergy indices of upper hierarchy showed that regardless of person conditions (One-person vs. Inter-person), the force stabilizing synergy indices ($\triangle V_{Force}^{UH}$) were negative values while the torque stabilizing synergy indices ($\triangle V_{Torque}^{UH}$) were positive. This result revealed because mathematically, force and torque stabilizing synergy indices have an inverse relationship in terms of two motor elements combinations (Latash et al., 2001). However $V\_UCM_{Torque}^{UH}$ and $V\_ORT_{Torque}^{UH}$, which are important factors in calculating the synergy indices, were higher in inter-person condition than one-person condition. This is because the change in forces of one person, which was induced by two person's controlling the torque together, might act as unexpected perturbation to the counterpart who can't control both hands simultaneously. Therefore those two person would have used the control strategy that form varied combination of forces within solution space to deal with the unpredictable torque errors (Fig.14).

4.2. Effect of feedback modalities on person difference

When somebody is holding a cup of water in a moving bus, you would spill the water if you cannot process information about the location of the cup which keeps changing. In this situation, sensory feedback is an important medium that corrects discrepancies between the expected and actual motor outputs during a motor task (Koh et al., 2015, Davis, 2007). Especially visual and somatosensory information plays an essential role in human movements (Hermsdörfer et al., 2008, Scheidt et al., 2005).

Consistently, the current results of RMSE showed that overall $RMSE_{Force}$ and $RMSE_{Torque}$ in one-person condition were reduced when both the visual and somatosensory feedback were provided (unstable condition). According to the Bayesian theory, information from multiple sensory modalities are independently perceived through individual sensory organs, but synergistically integrated to improve the recognition of the body state (McDonald et al., 2000). Thus, the integration of visual and somatosensory information perceived from two hands might be important to adjust the net force and maintain the net torque when performing the task by oneself.

In the inter-person condition, different from the results in one-person condition, when additional somatosensory feedback was provided (unstable condition), $RMSE_{Force}$ increased, while $RMSE_{Torque}$ decreased. It implies that even though multiple sensory information was provided, those two persons with independent motor systems were unable to control those two performance variables simultaneously and successfully. It might because both the magnitude and its change of the net torque can be physically sensed by the somatosensory feedback. On the other side, only the current magnitude without its change of the net forces can be sensed by the visual feedback, since the forces produced by the counterpart can't be physically sensed. In order to solve the problem that the change of net force can't be sensed in inter-person condition, a possible strategy is to maintain the net torque and adjust the magnitude of the net force. Therefore, the balance of the net torque might be a high priority and lead to a decreased $RMSE_{Torque}$ when multiple sensory feedback was provided.

The results of UCM analysis supported the idea above. When providing visual and somatosensory feedback together (unstable condition), the torque stabilizing synergy indices between both hands ($\triangle V_{Torque}^{UH}$) were greater in inter-person condition than one-person condition. This result associated with that $V\_UCM_{Torque}^{UH}$ was significantly increased in inter-person condition. It means that additional somatosensory information serves to create more positive co-variation of forces between both hands to maintained the torque balance under inter-person condition. However, the increased $V\_UCM_{Torque}^{UH}$ mathematically increase the $V\_ORT_{Force}^{LH}$, which means greater changes of force on lower hierarchy (Latash et al., 2008, Gorniak et al., 2009, Gorniak et al., 2007). In other words, the increased co-variation patterns to keep the net torque between both hands leads to elevated force variability of individual finger within each hand. This is consistent with the increased $RMSE_{Force}$. That is, those two person with independent motor system wouldn't have been able to control the total force in response to unpredictable force variability of individual finger caused by counterpart. In summary, When performing the motor task with another person, the somatosensory information was supposed to build a strategy in which the stable and balance of the net torque were considered more than the net force.

*4.3. Stronger effect of person * feedback interaction at MVC 30%*

According to previous studies, as the target force level increased from MVC 10% to MVC 40%, the effect of sensory information on the coordination patterns of bimanual increased to compensate the force errors (Hu et al., 2011). This tendency was more pronounced when the motor task was conducted with another person in this study. When the somatosensory feedback was allowed in addition to visual feedback in MVC 30% condition, the amount of error reduction for net torque between both hands ($RMSE_{Torque}$) was greater in inter-person condition than one-person condition. In addition, the torque stabilizing synergy indices ($\triangle V_{Torque}^{UH}$) between both hands significantly increased in inter-person condition compared to in one-person condition as multiple sensory feedback was provided.

These observations have potentially important implications for basic research on control strategies between two persons. According to previous studies, increased target force level contributed to changes in the force regularity or coordination pattern of motor elements (Singh et al., 2010, Hu and Newell, 2011). Therefore as the target force level of the motor task conducted by two person together increases, the force irregularity occurring between two persons with independent motor systems might elevated further. This might cause result in failure to maintain the net torque between both hands at the high target force level of the motor task and increase performance error. (see Fig.4 & Fig.5). At this time, somatosensory feedback which can physically sense the error information of net torque, plays an important role in properly controlling the commands between independent central nervous systems (CNS) to balancing the forces between both hands. Therefore, when performing the motor task with another person, it is considered that there is a threshold of force level that actively utilizes somatosensory feedback to maintain net torque between both hands. In this study, it is estimated to be MVC 30%, which is relatively higher force level than MVC 10%, 20%.

Chapter 5. CONCLUSION

The main purpose of the present study was to investigate the difference of control strategies between one-person and inter-person condition depending on the feedback modalities when performing the motor task. when two persons conducted together to the motor task that required simultaneous control of the force and torque between both hands, it was difficult for them to control both mechanical variables with visual feedback only. However, when somatosensory feedback was additionally provided compared to when visual feedback was provided only, the error reduction of net torque ($RMSE_{Torque}$) and the torque stabilizing synergy indices ($\triangle V_{Torque}^{UH}$) between both hands of two persons increased significantly. This tendency was noticeable at MVC 30%, which is relatively higher force level than MVC 10%, 20%. These results of current study suggested that visual and somatosensory feedback play an important role to overcome the physical constraints between two persons who has independent motor system. It is also considered that a threshold of force level exists that two persons actively utilize multiple sensory feedback to perform stably the motor task.

However, since the present study mainly interpreted the mechanical outcomes of the end effectors (e.g., fingers), there are limitations in that it is difficult to directly identify the changes in motor command transmitted from the two CNSs depending on the feedback modalities. Therefore, a follow-up study will require systematic hierarchical analysis to consider the changes in muscle activity as well as brain activity in order to clearly identify changes in control strategies between independent CNSs depending on the feedback modalities.

Bibliography

BOSGA, J. & MEULENBROEK, R. G. 2007. Joint-action coordination of redundant force contributions in a virtual lifting task. Motor Control, 11, 235-258.

BURSTEDT, M., EDIN, B. B. & JOHANSSON, R. S. 1997. Coordination of fingertip forces during human manipulation can emerge from independent neural networks controlling each engaged digit. Experimental brain research, 117, 67-79.

CHRISTENSEN, K. A. 2017. The Organization of Motor Synergies in One-Person and Two-Person Multi-Finger Force Production Tasks.

DAVIS, N. J. 2007. Memory and coordination in bimanual isometric finger force production. Experimental Brain Research, 182, 137-142.

EILS, E., CAóAL-BRULAND, R., SIEVERDING, L., DE LUSSANET, M. H. & ZENTGRAF, K. 2017. Vision adds to haptics when dyads perform a whole-body joint balance task. Experimental brain research, 235, 2089-2102.

FERRAND, L. & JARIC, S. 2006. Force coordination in static bimanual manipulation: Effect of handedness. Motor Control, 10, 359-370.

FINE, J. M., GIBBONS, C. T. & AMAZEEN, E. L. 2013. Congruency effects in interpersonal coordination. Journal of experimental psychology: Human Perception and Performance, 39, 1541.

GORNIAK, S. L., ZATSIORSKY, V. M. & LATASH, M. L. 2007. Emerging and disappearing synergies in a hierarchically controlled system. Experimental brain research, 183, 259-270.

GORNIAK, S. L., ZATSIORSKY, V. M. & LATASH, M. L. 2009. Hierarchical control of static prehension: II. Multi-digit synergies. Experimental brain research, 194, 1-15.

HERMSDøRFER, J., ELIAS, Z., COLE, J., QUANEY, B. & NOWAK, D. 2008. Preserved and impaired aspects of feed-forward grip force control after chronic somatosensory deafferentation. Neurorehabilitation and neural repair, 22, 374-384.

HU, X., LONCHARICH, M. & NEWELL, K. M. 2011. Visual information interacts with neuromuscular factors in the coordination of bimanual isometric force. Experimental brain research, 209, 129-138.

HU, X. & NEWELL, K. M. 2011. Adaptation to bimanual asymmetric weights in isometric force coordination. Neuroscience letters, 490, 121-125.

KNOBLICH, G., JORDAN, J. S. J. J. O. E. P. L., MEMORY, & COGNITION 2003. Action coordination in groups and individuals: Learning anticipatory control. 29, 1006.

KODAMA, K., FURUYAMA, N. & INAMURA, T. 2015. Differing dynamics of intrapersonal and interpersonal coordination: two-finger and four-finger tapping experiments. PloS one, 10.

KOH, K., KWON, H. J., YOON, B. C., CHO, Y., SHIN, J.-H., HAHN, J.-O., MILLER, R. H., KIM, Y. H. & SHIM, J. K. 2015. The role of tactile sensation in online and offline hierarchical control of multi-finger force synergy. Experimental brain research, 233, 2539-2548.

LATASH, M. L., GORNIAK, S. & ZATSIORSKY, V. M. 2008. Hierarchies of synergies in human movements. Kinesiology: International journal of fundamental and applied kinesiology, 40, 29-38.

LATASH, M. L., SCHOLZ, J. F., DANION, F. & SCHøNER, G. 2001. Structure of motor variability in marginally redundant multifinger force production tasks. Experimental brain research, 141, 153-165.

LATASH, M. L., SCHOLZ, J. P. & SCHøNER, G. 2002. Motor control strategies revealed in the structure of motor variability. Exercise and sport sciences reviews, 30, 26-31.

LATASH, M. L., SCHOLZ, J. P. & SCHøNER, G. 2007. Toward a new theory of motor synergies. Motor control, 11, 276-308.

MASON, A. H. & MACKENZIE, C. L. 2005. Grip forces when passing an object to a partner. Experimental brain research, 163, 173-187.

MCDONALD, J. J., TEDER-SAÈLEJAÈRVI, W. A. & HILLYARD, S. A. 2000. Involuntary orienting to sound improves visual perception. Nature, 407, 906-908.

PARK, J., WU, Y.-H., LEWIS, M. M., HUANG, X. & LATASH, M. L. 2012. Changes in multifinger interaction and coordination in Parkinson's disease. Journal of neurophysiology, 108, 915-924.

PASSOS, P., LACASA, E., MILHO, J. & TORRENTS, C. 2020. Capturing Interpersonal Synergies in Social Settings: An Example within a Badminton Cooperative Task. Nonlinear dynamics, psychology, and life sciences, 24, 59.

PASSOS, P., MILHO, J. & BUTTON, C. 2018. Quantifying synergies in two-versus-one situations in team sports: an example from Rugby Union. Behavior research methods, 50, 620-629.

RESCHECHTKO, S., ZATSIORSKY, V. M. & LATASH, M. L. 2015. Task-specific stability of multifinger steady-state action. Journal of motor behavior, 47, 365-377.

ROMERO, V., KALLEN, R., RILEY, M. A. & RICHARDSON, M. J. 2015. Can discrete joint action be synergistic? Studying the stabilization of interpersonal hand coordination. Journal of Experimental Psychology: Human Perception and Performance, 41, 1223.

SCHEIDT, R. A., CONDITT, M. A., SECCO, E. L. & MUSSA-IVALDI, F. A. 2005. Interaction of visual and proprioceptive feedback during adaptation of human reaching movements. Journal of neurophysiology, 93, 3200-3213.

SCHOLZ, J. P., KANG, N., PATTERSON, D. & LATASH, M. L. 2003. Uncontrolled manifold analysis of single trials during multi-finger force production by persons with and without Down syndrome. Experimental Brain Research, 153, 45-58.

SINGH, T., SKM, V., ZATSIORSKY, V. M. & LATASH, M. L. 2010. Fatigue and motor redundancy: adaptive increase in finger force variance in multi-finger tasks. Journal of neurophysiology, 103, 2990-3000.

SLOMKA, K., JURAS, G., SOBOTA, G., FURMANEK, M., RZEPKO, M. & LATASH, M. L. 2015. Intra-personal and inter-personal kinetic synergies during jumping. Journal of human kinetics, 49, 75-88.

SOFIANIDIS, G., HATZITAKI, V., GROUIOS, G., JOHANNSEN, L. & WING, A. 2012. Somatosensory driven interpersonal synchrony during rhythmic sway. Human movement science, 31, 553-566.

SOLNIK, S., RESCHECHTKO, S., WU, Y. H., ZATSIORSKY, V. M. & LATASH, M. L. 2015. Force-stabilizing synergies in motor tasks involving two actors. Exp Brain Res, 233, 2935-49.

SOLNIK, S., RESCHECHTKO, S., WU, Y. H., ZATSIORSKY, V. M. & LATASH, M. L. 2016. Interpersonal synergies: static prehension tasks performed by two actors. Exp Brain Res, 234, 2267-82.

STOFFREGEN, T. A., GIVEANS, M. R., VILLARD, S., YANK, J. R. & SHOCKLEY, K. 2009. Interpersonal postural coordination on rigid and non-rigid surfaces. Motor Control, 13, 471-483.

VAN DER WEL, R. P., KNOBLICH, G. & SEBANZ, N. 2011. Let the force be with us: dyads exploit haptic coupling for coordination. Journal of Experimental Psychology: Human Perception and Performance, 37, 1420.

국문초록

대인 상호작용 협응

- 다중 손가락을 이용한 힘, 토크 생성 시 감각 피드백 유형에 따른 협응 지수의 변화-

이성준
서울대학교 대학원
체육교육과
인간운동과학 전공

일상생활에서 행해지는 동작들은 대인 간의 상호작용 속에서 수행되어지는 경우가 많다. 대표적인 예시로 무거운 물체를 운반하는 동작, 악수하는 동작, 건배하는 동작 등을 손꼽을 수 있다. 이 때, 상대방으로부터 제공되는 운동학, 운동역학적 정보의 변화를 정확하게 예측하지 못한다면 움직임을 안정적으로 조정하기 어려울 것이다. 즉, 무거운 물체를 두 사람이 함께 드는 경우, 예기치 못한 상황에서 상대방이 생성하는 힘의 변화가 물체를 안정적으로 옮기는데 있어 방해요소로 작용할 수 있다. 따라서 선행연구에서는 두 사람이 함께 특정 동작을 안정적으로 수행하기 위해 대인 간에 공유하는 피드백의 중요성을 강조하고 있다. 하지만 아직까지 독립적인 운동 시스템을 지닌 두 사람이 함께 과제를 수행할 시, 피드백의 유형에 따른 상호 제어전략의 변화에 관한 연구는 미비한 실정이다. 이에 본 연구의 목적은 피드백 유형에 따른 개인 및 대인 간의 과제수행 변화와 제어전략의 차이를 규명하는 것이다. 본 연구에 참여한 모든 피험자는

양 손이 생성하는 힘이 좌,우로 편중되지 않은 상태로 양 손의 합력을 목표 힘값 (최대 자발적 수축력의 10%, 20%, 30%)에 맞춰 최대한 일정하게 생성하는 과제를 수행하였다. 이와 같은 과제를 개인 및 대인 조건과 시각 피드백, 시각 피드백&체성감각 피드백 조건으로 분류하여 반복 측정하였다. 연구 결과, 시각 피드백만 제공한 조건에서 두 사람이 함께 과제를 수행할 시, 양 손의 균형(넷토크)과 합력을 일정하게 유지하는 것이 혼자서 수행하는 것에 비해 더 어려운 것으로 나타났다. 하지만 추가적인 체성감각 피드백이 제공됨에 따라 두 사람 간의 오른손, 왼손의 균형을 유지하기 위한 양 손의 협응 지수가 혼자서 수행했을 때에 비해 상대적으로 크게 증가하였으며, 이로 인해 양 손 사이의 넷토크에 대한 제곱 평균 제곱근 오차도 상대적으로 크게 감소하였다. 이러한 경향은 과제의 목표 힘값이 최대 자발적 수축력의 10%, 20%에 비해 상대적으로 큰 30% 조건에서 더욱 두드러지는 것으로 나타났다. 따라서 상대적으로 큰 힘을 필요로 하는 특정 동작을 두 사람이 함께 안정적으로 수행하기 위해서는 시각 정보와 더불어 체성감각 정보가 제공되어야 하며, 이와 같은 다중감각 정보는 독립적인 운동 시스템을 지닌 두 사람 사이의 물리적인 제약조건을 극복하기 위한 중요한 매개 요인임을 확인하였다.

주요어 : 대인 상호작용, 시각 피드백, 체성감각 피드백, 제곱 평균 제곱근 오차, 협응 지수, 넷토크

학 번 : 2018-21948