KJSB

Korean Journal of Sport Biomechanics 2016; 26(2): 175-181
http://dx.doi.org/10.5103/KJSB.2016.26.2.175
http://e-kjsb.org eISSN 2093-9752

ORIGINAL

Age-related Changes in Multi-finger Synergy during Constant Force Production with and without Additional Mechanical Constraint

Yang Sun Park[1,2,3], Hyun Joon Kwon[3], Kyung Koh[2,3], Jae Kun Shim[3,4,5,6]

[1]Department of Physical Education, College of Performing Arts and Sports, Hanyang University, Seoul, South Korea
[2]The Movement Science Center of Research Institute for Sports Science and Sports Industry, Hanyang University, Seoul, South Korea
[3]Department of Kinesiology, School of Public Health, University of Maryland, College Park, MD, USA
[4]Department of Mechanical Engineering, Kyunghee University, Global Campus, Kyung-gi, South Korea
[5]Fischell Department of Bioengineering, University of Maryland, College Park, MD, USA
[6]Neuroscience and Cognitive Science (NACS) Program, University of Maryland, College Park, MD, USA

Received : 05 May 2016
Revised : 02 June 2016
Accepted : 10 June 2016

Corresponding Author
Jae Kun Shim
Department of Kinesiology/Fischell Department of Bioengineering/ Neuroscience and Cognitive Science (NACS) Program University of Maryland, College Park 0110F SPH Building, College Park, MD 20742
Tel : +302-405-2492
Fax : +301-405-5578
Email : jkshim@umd.edu

Objective: The aim of this study was to investigate age-related changes of multi-finger synergy during a constant force production task with and without an additional mechanical constraint.

Method: Fourteen elderly subjects (age: 78.50 ± 4.63 yrs, height: 157.29 ± 8.97 cm, weight: 65.13 ± 6.93 kg) and 14 young subjects (age: 21.13 ± 1.35 yrs, height: 171.57 ± 8.43 cm, weight: 70.29 ± 16.77 kg) participated in this study. The subjects were asked to place their index and middle fingers on two force transducers fixed on a small non-moving teeterboard and produce 10 N by pressing the sensors while watching force feedback on a computer screen under the no additional constraint condition (NAC). The subjects also performed the same task with an additional mechanical constraint (AC) where the subjects were asked to balance a teeterboard that could be rotated by finger forces. An uncontrolled manifold approach was used to calculate within-trial and between-trial multi-finger synergy indices, variance in uncontrolled subspace (V_{UCM}), and variance in subspace orthogonal to UCM subspace (V_{ORT}). Two-way repeated measured ANOVA was performed with the within-factor of task condition (with and without an additional constraint) and the between factor of groups (elderly and young).

Results: The elderly group showed significantly increased within-trial V_{ORT} in AC compared with NAC ($p < .05$) while the young group showed no significant difference between AC and NAC. There was no significant group difference for within-trial V_{UCM}. Between-trial V_{ORT} remained unchanged between groups and conditions. However, between-trial V_{UCM} for the elderly group significantly decreased in AC as compared to NAC, along with no significant difference for the young group. For multi-finger synergy, there was no significant group difference of within-trial synergy. However, between-trial synergy for the elderly group significantly decreased in AC as compared to NAC ($p < .05$).

Conclusion: Our results indicate that aging decreased consistency (i.e., ability to perform the task on a moment-to-moment basis) with an additional mechanical constraint. In addition, aging was associated with decreased multi-finger synergy on a trial-to-trial basis.

Keywords: Finger, Synergy, Uncontrolled manifold, Aging

INTRODUCTION

Movements of the human body are generated through interactions between various elements, such as bones, muscles, and nerves. In particular, motor redundancy is created when more elements than the minimal elements needed for the movement are involved (Bernstein, 1967). Such motor redundancy has been suggested as a problem that must be solved by the central nervous system (CNS) to control movement (Bernstein, 1967; Turvey, Shaw, & Mace, 1978). According to a recent study (Ambike, Mattos, Zatsiorsky, & Latash, 2016; Karol et al., 2011), the CNS resolves the problem of motor redundancy through the collaborative relationship between the basic elements involved in movement. However, many experimental bases have suggested that motor redundancy should not be perceived as a problem to be solved by the CNS; but rather, it should be replaced by motor abundance, which is a concept of the same movement being expressed through various combinations of basic elements. This concept can be explained by the term "motor synergy" and it can be viewed as various forms of synergy between basic elements of movement, such as muscles and joints, for successful motor task performance (Gelfand & Latash, 1998; Latash & Zatsiorsky, 2009).

Uncontrolled manifold (UCM) analysis is a method that can quantify motor synergy in detail and is used to analyze the variability of basic elements caused by motor redundancy for understanding of the mechanism by which the CNS controls movement. This analytic method uses the relationship between the basic elements involved in movement and motor performance tasks to calculate the variability of the basic elements as task-irrelevant variability (variance in UCM subspace, V_{UCM}) and task-relevant variability (meaning, type of error; variance in subspace orthogonal to UCM subspace, V_{ORT}) (Shim, Park, Kim, & Kim, 2011). Motor synergy, in many cases, can be quantified by the difference between these two variances (V_{UCM}-V_{ORT}) or by similar methods, and motor synergy increases when the task-irrelevant variability increases or the task-relevant variability decreases. There have been multi-faceted efforts to use UCM analysis to identify human motor synergy (Hooke, Karol, Park, Kim, & Shim, 2012; Shim, Lay, Zatsiorsky, & Latash, 2004; Shim et al., 2011). In particular, task-irrelevant variability appears larger than variance in multi-finger control, and this was identified as multi-finger synergy for successful task performance (Shim et al., 2004; Latash, Scholz, & Schoner, 2007).

Motor synergy is analyzed at two levels, within-trial and between-trial, to show diverse aspects of control (Koh et al., 2015; Scholz, Kang, Patterson, & Latash, 2003). Within-trial analysis was used to study the moment-to-moment interactions of basic elements for successful task performance (Tuller, Turvey, & Fitch, 1982), while between-trial analysis was used to study various interactions of basic elements during repeat performances of the same task. For example, in a task that requires the use of the index and middle fingers to produce a sum force of 10 N, the interaction between the two fingers to maintain 10 N in real time is measured via within-trial analysis, while the various combinations of the two fingers during repeat performance of this task is measured via between-trial analysis. Precedent studies mostly studied synergy mechanisms through between-trial analysis (Shim et al., 2004; Park, Singh, Zatsiorsky, & Latash, 2012). However, according to Scholz & Schoner (1999), between-trial and within-trial motor analyses are analyzing other controlling capabilities of the CNS (Scholz & Schöner, 1999).

Studies related to motor synergy have continued with focus on the fact that motor coordination and control are reduced in the elderly (Park, Sun, Zatsiorsky, & Latash, 2011; Shim et al., 2004). Finger-related muscle weakness in the elderly comes from a decreased number of motor units, which is known to be attributed to progression of neural redistribution from slowed movement (Grabiner & Enoka, 1995; Larsson & Ansved, 1995). Consequently, as the ability to control the fingers becomes weaker, the ability to use the hand to grab objects also diminishes (Enoka et al., 2003; Ranganathan, Siemionow, Sahgal, & Yue, 2001). Shim, Lay, Zatsiorsky, & Latash (2004) reported that when the elderly used five fingers to perform the task of grabbing an object, task-relevant variability or motor task performance error increased (Shim et al., 2004), while Shinohara et al. (2004) reported that with respect to the ability for the elderly to have complex control over their fingers, the elderly have weakened coordination for controlling signals, which reduces maximum voluntary contraction (MVC) (Shinohara, Scholz, Zatsiorsky, & Latash, 2004). According to the study by Voelcker-Rehage, Stronge, & Alberts (2006), when the elderly were given a task under two different constraint conditions there were decreases in cognitive and motor performance, and this induced a bigger variability into the task of tracking force, creating cognitive and task performance errors, which reduced the task performance capabilities of the elderly (Voelcker-Rehage, Stronge, & Alberts, 2006). The prior studies mentioned above show that motor performance in the elderly decreases as V_{ORT} increases. In other words, motor synergy for completing a task is created from a combination of V_{ORT} and V_{UCM}, and questions on what effects V_{UCM} has when the elderly are presented with a more complex environment for task performance and what effects are ultimately had on synergy have not yet been accurately identified. In particular, despite the fact that motor redundancy occurs when the number of basic motor elements is greater than the number of motor constraints, understanding of the mechanism associated with changes in motor synergy in the elderly based on the number of motor constraints or their forms is still lacking, which indicates the necessity of this study.

The purpose of this study was to examine elderly and young participants for changes in within-trial and between-trial multi-finger synergy during performance of a constant force production task under two different constraint conditions (with no additional mechanical constraint vs. with additional mechanical constraint).

METHODS

1. Participants

Participants in this study included 15 college students, 7 women and 8 men (mean age: 21.13 ± 1.35 yrs, height: 171.57 ± 8.43 cm, and weight: 70.29 ± 16.77 kg) and 14 elderly, 10 women and 4 men (mean age: 78.50 ± 4.63 yrs, height: 157.29 ± 8.97 cm, and weight: 65.13 ± 6.93 kg), who did not have any musculoskeletal abnormalities in their lower extremities. All participants were given explanations on the experimental procedures and their written consent was received prior to participation.

2. Procedures

Participants in this study were instructed to produce 10 N of force using their middle fingers and they were able to see in real time the force generated from their two fingers and the target force value through graphs displayed on a monitor at eye level. In order to control the use of joints related to the right hand during operation, the wrist and fingers were kept at the same height, as shown in Figure 1A, and a wrist joint control device that prevented use of the wrist was installed. Target performance time was set to 10 s and each individual performed the task 10 times each. Two force sensors (Models 208 M182 and 484B, Piezotronics, Inc., Depew, NY) were used to measure the force produced by the fingers. Two different experimental conditions were presented: one with an additional mechanical constraint (AC) and one with no additional mechanical constraint (NAC). The NAC condition was the condition where the sum of the force generated by the two fingers was measured using two sensors above the fixture (Figure 1B), while the AC condition was the condition where the sum of the force gene-

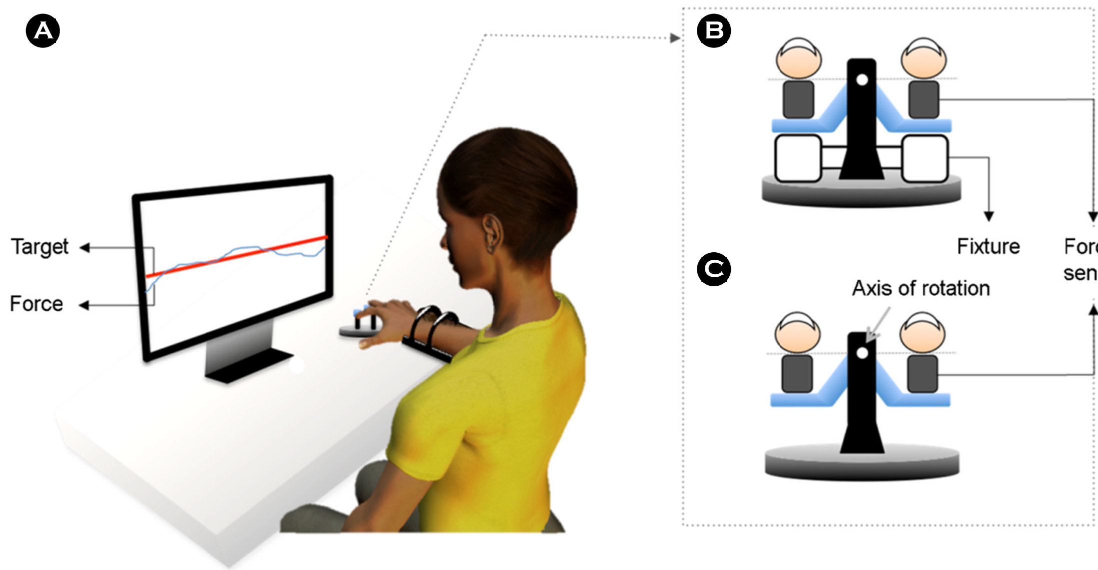

Figure 1. (A) Schematic illustration of the experimental setup, (B) the 10 N force production task with no additional constraint (NAC), and (C) the task with an additional constraint (AC). Subjects were required to balance the teeterboard for the AC condition in addition to producing 10 N.

rated by the two fingers was measured using two sensors on a rotating surface (Figure 1C). Here, the axis of rotation was designed to be consistent with the plane where the fingers touched the surface of the sensors (Figure 1C). The goal of this design was to minimize the value of torque generated from tangential force.

3. Data processing

In this study, the values for force generated during task performance, stabilized for 3 to 9 sec, were analyzed (Koh et al., 2015). Variances that affected and did not affect motor performance were quantified using between-trial and within-trial analysis (Koh et al., 2015).

The sum of force from each finger, F_{TOT}, was expressed as a function of time, t, and task, T.

$$F_{TOT}(t,T) = F_I(t,T) + F_M(t,T)$$

Here, $F_I(t,T)$ and $F_I(t,T)$ represent force from the thumb and index finger, respectively.

Force of the fingers is an independent function of t and T, which can be expressed as the following:

$$F_{TOT}(t,T) = m_{TOT}(T) + x_{TOT}(t) = \sum_{i=\{I,M\}} m_i(T) + x_i(t)$$

Here, m(T) is the mean force in task T and x(t) is the force that makes real-time changes to the value of m(T) from the center, while i represents each finger (I: index, M: middle).

1) Within-trial analysis

In the following equation, $x_{TOT}(t) = x_I(t) + x_M(t)$,

Variance that affects motor performance, $V_{ORT\_within-trial}$, is calculated in the following manner.

$$V_{ORT\_within-trial} = \frac{var(x_{TOT}(t))}{dof}$$

Here, $var(\cdot)$ is the variance and dof is the number of fingers used during task performance ($dof = 2$).

Variance that does not affect motor performance, $V_{UCM\_within-trial}$, is as follows.

$$V_{UCM\_within-trial} = \sum_{i=\{I,M\}} var(x_i(t)) - \frac{var(x_{TOT}(t))}{2}$$

Within-trial multi-finger synergy, $Syn_{within-trial}$, is defined as follows:

$$Syn_{within-trial} = \frac{V_{UCM\_within-trial} - V_{ORT\_within-trial}}{V_{UCM\_within-trial} + V_{ORT\_within-trial}}$$

2) Between-trial analysis

Just as in within-trial analysis, using the equation $m_{TOT}(T) = m_I(T) + m_M(T)$,

Variance that affects motor performance, $V_{ORT\_between-trial}$, and variance that does not affect motor performance, $V_{UCM\_between-trial}$, are calculated using

$$V_{ORT\_within-trial} = \frac{var(m_{TOT}(T))}{2},$$

Between-trial multi-finger synergy, $Syn_{within-trial}$, is defined as follows:

$$Syn_{between-trial} = \frac{V_{UCM\_between-trial} - V_{ORT\_between-trial}}{V_{UCM\_between-trial} + V_{ORT\_between-trial}}$$

Table 1. Results of post hoc of $V_{ORT\_within-trial}$ and $V_{ORT\_between-trial}$ of two conditions (unit: N^2)

	Within-trial			Between-trial		
	NAC	AC	*t*-value	NAC	AC	*t*-value
Young	0.17 ± 0.12	0.21 ± 0.13	0.814	0.003 ± 0.003	0.003 ± 0.004	0.603
Elderly	0.40 ± 0.66	0.08 ± 0.07	**2.645***	0.008 ± 0.011	0.020 ± 0.032	1.446
t-value	1.334	**2.836***		1.716	1.918	

*significant at p < .05.

Table 2. Results of post hoc of $V_{UCM\_within-trial}$ and $V_{UCM\_between-trial}$ of two conditions (unit: N^2)

	Within-trial			Between-trial		
	NAC	AC	*t*-value	NAC	AC	*t*-value
Young	0.057 ± 0.102	0.005 ± 0.008	2.094	0.23 ± 0.18	0.03 ± 0.02	4.399**
Elderly	0.047 ± 0.039	0.013 ± 0.016	**3.114****	0.81 ± 0.77	0.07 ± 0.09	**3.504****
t-value	0.332	1.489		**2.728***	1.636	

Significant at *p < .05, **p < .01

4. Statistical analysis

In this study, all statistical analyses were performed using SPSS 21.0 (IBM, USA) and ANOVA with repeated measures to analyze the differences in synergy between the two age groups (elderly and young) and according to the two experimental conditions (single and dual tasks). A simple post hoc test was performed for interactions based on significant differences, while an independent *t*-test and paired *t*-test were performed according to age groups and experimental conditions, respectively. The significance level for all values was set to p < .05.

RESULTS

1. Results of variance that affect motor performance V_{ORT}

$V_{ORT\_within-trial}$ analysis results showed significant differences in the main effects of Task (F = 9.100, p = .008) and Group (F = 5.507, p = .027), and interaction Task × Group (F = 5.401, p = **.028**). The results of the simple effect test for the *post hoc* test of interactions are shown in Table 1 and Figure 2.

$V_{ORT\_between-trial}$ analysis results showed no significant differences in main effects of Task (F = 2.476, p = .127) or interactions Task × Group (F = 1.913, p = .178), but significant differences in the main effect of Group (F = 5.190, p = .031). The results of the simple effect test for the *post hoc* test are shown in Table 1 and Figure 2.

2. Results of variance that does not affect motor performance (V_{UCM})

$V_{UCM\_within-trial}$ analysis results showed significant differences in the main effects of the Task (F = 9.682, p = .004) but no significant differences in the main effects of Group (F = 0.006, p = .940) or interaction Task × Group (F = 0.380, p = .543). The results of the simple effect test for the *post hoc* test are shown in Table 2 and Figure 2.

$V_{UCM\_between-trial}$ analysis results showed significant differences in the main effects of the Task (F = 20.260, p = .000) and Group (F = 9.197, p = .005), and interaction Task × Group (F = 6.621, p = .016). The results of the simple effect test for the *post hoc* test are shown in Table 2 and Figure 2.

3. Multi-finger synergy results

$Syn_{within-trial}$ analysis results showed significant differences in the main effects of the Task (F = 206.522, p = .000), but no significant differences in the main effects of Group (F = 0.178, p = 0.676) or interaction Task × Group (F= 0.339, p = .565).

$Syn_{between-trial}$ analysis results showed significant differences in the main effects of Task (F = 30.051, p = .000) and Group (F = 4.243, p = .049), and interaction Task × Group (F = 4.769, p = .038). The results of the simple effect test for the post hoc test are shown in Table 3 and Figure 3.

DISCUSSION

Variance that directly affects motor performance (V_{ORT}) represents the calculated value of how big the error is when the index and middle fingers cooperate to perform the task of joining each other. Ultimately, the value of task-relevant variance becoming larger can be interpreted as greater interference on the performance to achieve the task goal. The within-trial analysis results from the present study show a significant difference in interaction according to the two conditions given to the elderly and young (p = .028), and based on these results, it was determined that the elderly had diminished consistency, which is the ability to maintain the within-trial task under the dual task conditions. Simple

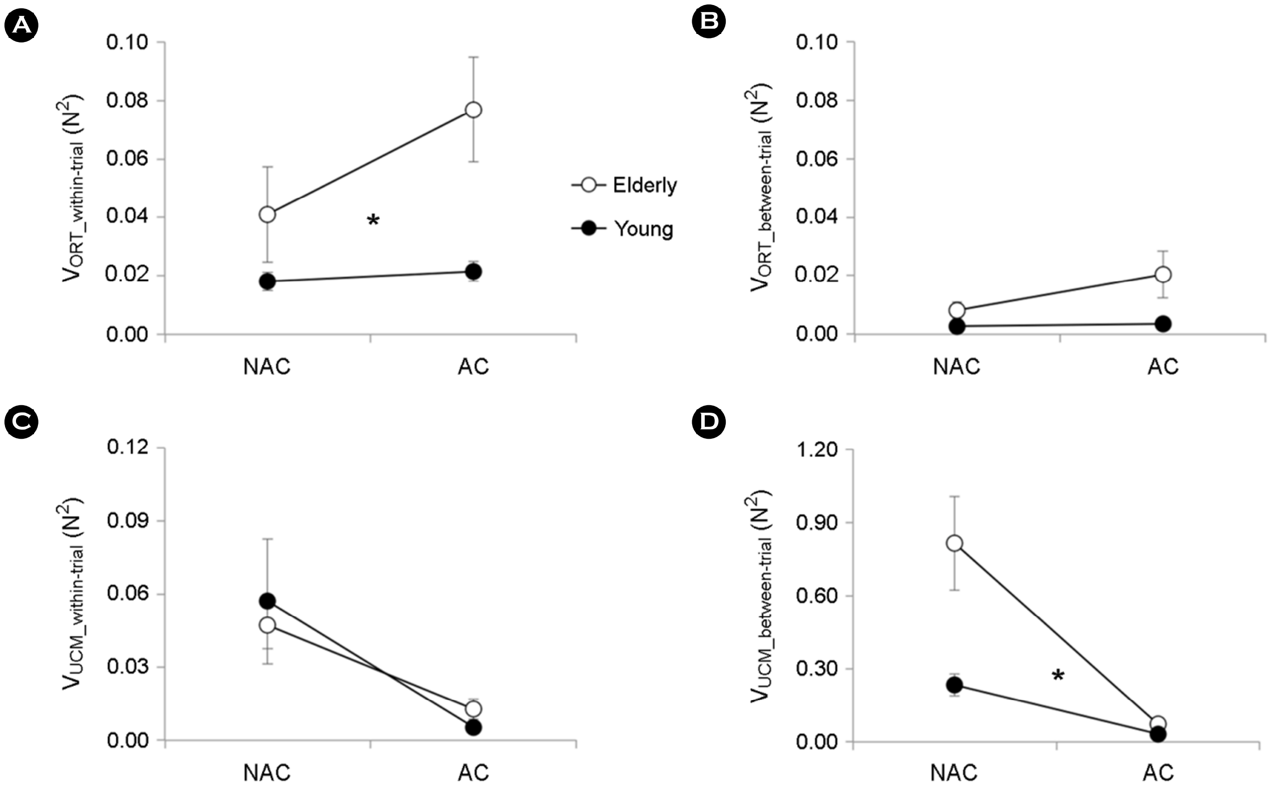

Figure 2. Within-trial V_{ORT} (A), between-trial V_{ORT} (B), within-trial V_{UCM} (C) and between-trial V_{UCM} (D) are shown for each age group (Elderly: solid symbols and Young; open symbols) for the two task conditions (NAC: with no additional mechanical constraint and AC: with additional mechanical constraint). Means of participants' data are shown with standard error bars. Statistical significance effects of the interaction (*, $p < .05$; interaction between group and task) were calculated using repeated measures ANOVA. Asterisk indicates a statistical difference between groups.

Table 3. Results of post hoc $V_{Syn\_within\text{-}trial}$ and $V_{Syn\_between\text{-}trial}$ by two tasks (unit: N^2)

	Within-trial			Between-trial		
	Single task	Dual task	*t*-value	Single task	Dual task	*t*-value
Young	0.24 ± 0.30	-0.70 ± 0.27	**11.676*****	0.98 ± 0.30	0.79 ± 0.17	**4.151****
Elderly	0.17 ± 0.34	-0.70 ± 0.19	**8.892*****	0.96 ± 0.07	0.53 ± 0.43	**4.058****
t-value	0.604	0.013		0.554	**2.140***	

Significant at *$p < .05$, **$p < .01$, ***$p < .0001$

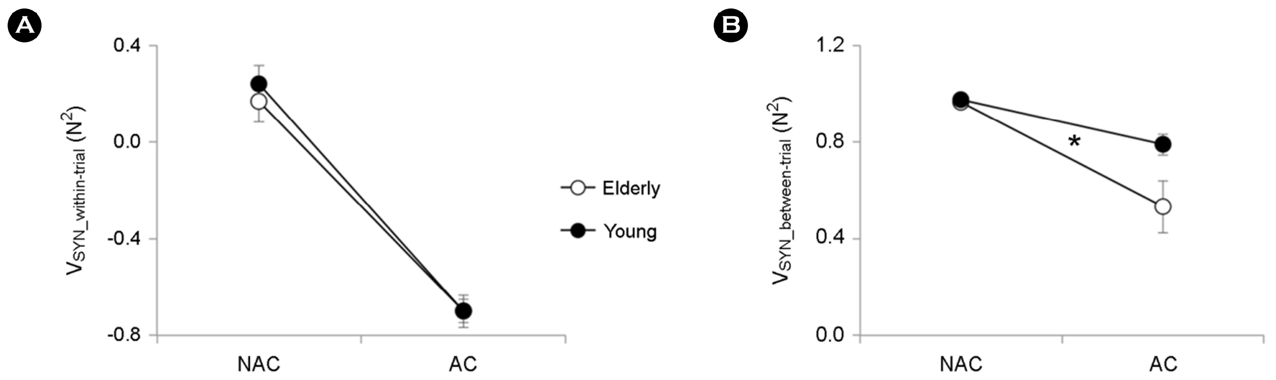

Figure 3. $Syn_{within\text{-}trial}$ (A), $Syn_{between\text{-}trial}$ (B) are shown for each age group (Elderly: open symbols and Young; solid symbols) between the two task conditions (NAC: with no additional mechanical constraint and AC: with additional mechanical constraint). Mean of the participants' data are shown with standard error bars. Statistical significance effects of the interaction (*, $p < .05$; interaction between group and task) were calculated using repeated measures ANOVA. Asterisk indicates a statistical difference between groups.

effect test results showed no difference in task performance between the elderly and young under the NAC condition, but under the AC condition, the elderly had a significantly higher value of errors occurring during motor performance than the young, thereby showing an interaction. In short, we learned that the elderly and young do not have differences in motor performance under the NAC condition (Olafsdottir, Zhang, Zatsiorsky, & Latash, 2007).

An interesting task-relevant variance result found in the present study was that between-trial analysis results did not show differences between the groups or differences in changes based on dual tasks. In other words, the elderly and young did not have differences in repeatability, which is the ability to repeat the same task during motor performance, and since both groups did not show changes in motor performance according to whether additional constraint elements were added or not, it was interpreted that even if the constraining environment is increased, motor performance repeatability does not decrease.

V_{UCM} is known as a variable that does not affect motor performance for achieving a task goal, or as a task-irrelevant variance value (Latash, Scholz, Danion, & Schöner, 2002; Shim et al., 2011). Analysis can be made from the perspective of how many combinations of movement-related elements (e.g., fingers, muscles, joints) are used or not used for goal achievement during motor performance (Shim et al., 2011). The fact that the task-irrelevant variance value calculated in the present study was high indicates that the two fingers made many combinations to achieve the task goal of producing 10 N, while having a low value would mean only a small number of combinations or simple combinations were made to perform the task. Among the experimental conditions designed for the study, the simple task environment was created so that a force value of 10 N can eventually be reproduced even if the sum force of 10 N is distributed unevenly between the index and middle fingers. Meanwhile, in the AC condition, an axis of rotation was established relative to the surface of the force sensor where the fingers touch, which created an environment in which the target force value cannot be achieved without force being evenly distributed between the two fingers. For example, if the index fingers continue to exert greater force than the middle finger during motor performance, the axis of rotation would continue to rotate inward, which would create an environment that makes reproduction of the sum force of 10 N difficult. Therefore, the within-trial and between-trial results for the dual task being close to 0 can be viewed as obvious results of the experimental design used in this study. In looking at this from the control perspective, the constraint condition of continuing to maintain 10 N and the constraint of maintaining the rotational balance of a seesaw structure represent two conflicting conditions (i.e. conflict of interest between sub-tasks), and as such, it can be viewed that the CNS used a mechanism of creating a solution by making the covariance be close to 0 in a situation where the two fingers cannot make a positive covariance nor negative covariance for successful task performance.

Moreover, within-task analysis showed significant differences in the elderly based on whether a constraint element was added or not, which can be attributed to the elderly having aging-related decreases in flexibility and the ability for the two fingers to cooperate in real-time (Koh et al., 2015). Moreover, appearances of interactions between the elderly and young for between-trial can be interpreted as the elderly using multiformity, namely, producing more diverse and complex forms of combinations with the two fingers, to a greater degree than the young under the NAC condition and having less reproducibility for repeating the motor performance. The fact that these results were seen only in between-trial analysis is an interesting finding in this study. Synergy is a variable that can explain the cooperative capability (is it a positive cooperation or a negative cooperation?) when two fingers engage in a motor performance for achieving the task goal (Shim et al., 2004; Latash et al., 2007). The synergy values can be divided into three categories for easier understanding: first, if the synergy value is a positive value, the two fingers interacted with each other while compensating for the errors (interpreted as the two fingers having positive synergy); if the value is close to 0, the two fingers were independent of each other; and if the synergy value is negative, the synergy the two fingers interacting with each other while amplifying the errors (interpreted as the two fingers having negative synergy).

The results of this study showed that under the NAC condition, both the elderly and young groups created positive synergy for motor performance by the two fingers in the within-trial of task goal achievement, while under the AC condition, they created negative synergy by showing a negative value. This can be interpreted as cooperation being formed successfully under the NAC condition, then changing to form a negative cooperation with each other when given a dual task. Moreover, the fact that the results did not show differences between the elderly and young can be interpreted as age having no effect on finger control within-trial.

On the other hand, interactions appeared in the between-trial, showing that both the elderly and young groups created positive synergy with no significant difference under the single task condition, but as the environment changed to a dual task environment, both the elderly and young groups showed decreases in synergy values. The results showed that the elderly had a more significant decrease in synergy than the young under the dual task condition (t = 2.140), which indicates that compared to the young, the elderly engage in motor performance with synergy that has independence from one finger to the other under an environment with increased constraints. Ultimately, the elderly, as compared to the young, have a decreased capability to have the two fingers generate synergy between each other when the task environment for repeated performance of a task becomes more complex.

CONCLUSIONS

The purpose of this study was to identify changes in multi-finger synergy by presenting the elderly and young participants with two different environmental conditions (simple task performance with a single motor constraint condition and dual task performance with two motor constraint conditions) for within-trial and between-trial tasks using fingers. As a result, the following conclusions were derived.

Within-trial multi-finger synergy showed no difference between the elderly and young for both conditions whether a constraint element was added or not. However, between-trial synergy showed decreased multi-finger synergy in the elderly as compared with the young when a constraint element was added. Therefore, aging causes a decrease in synergy, which is the ability to repeat performances of a task in various forms under complex task environments.

ACKNOWLEDGEMENTS

This study was supported by the National Research Foundation of Korea through grant funding from the Korean Government (Ministry of Science, ICT, and Future Planning) in 2012 (NRF-2012R1A6A3A04040457).

REFERENCES

Ambike, S., Mattos, D., Zatsiorsky, V. & Latash, M. (2016). Synergies in the space of control variables within the equilibrium-point hypothesis. *Neuroscience*, 315, 150-161.

Bernstein, N. A. (1967). The co-ordination and regulation of movements.

Enoka, R. M., Christou, E. A., Hunter, S. K., Kornatz, K. W., Semmler, J. G., Taylor, A. M. & Tracy, B. L. (2003). Mechanisms that contribute to differences in motor performance between young and old adults. *Journal of Electromyography and Kinesiology*, 13(1), 1-12.

Gelfand, I. M. & Latash, M. L. (1998). On the problem of adequate language in motor control. *Motor Control*, 2(4), 306-313.

Grabiner, M. D. & Enoka, R. M. (1995). Changes in movement capabilities with aging. *Exercise and Sport Sciences Reviews*, 23(1), 65 -104.

Hooke, A. W., Karol, S., Park, J., Kim, Y. H. & Shim, J. K. (2012). Handwriting: three-dimensional kinetic synergies in circle drawing movements. *Motor Control*, 16(3), 329-352.

Karol, S., Kim, Y.-S., Huang, J., Kim, Y. H., Koh, K., Yoon, B. C. & Shim, J. K. (2011). Multi-finger pressing synergies change with the level of extra degrees of freedom. *Experimental Brain Research*, 208(3), 359 -367.

Koh, K., Kwon, H. J., Yoon, B. C., Cho, Y., Shin, J. H., Hahn, J. O., . . . & Shim, J. K. (2015). The role of tactile sensation in online and offline hierarchical control of multi-finger force synergy. *Exp Brain Res*, 233(9), 2539-2548. doi: 10.1007/s00221-015-4325-6

Larsson, L. & Ansved, T. (1995). Effects of ageing on the motor unit. *Progress in Neurobiology*, 45(5), 397-458.

Latash, M. L., Scholz, J. F., Danion, F. & Schöner, G. (2002). Finger coordination during discrete and oscillatory force production tasks. *Experimental Brain Research*, 146(4), 419-432.

Latash, M. L., Scholz, J. P. & Schoner, G. (2007). Toward a new theory of motor synergies. *MOTOR CONTROL-CHAMPAIGN-*, 11(3), 276.

Latash, M. L. & Zatsiorsky, V. M. (2009). Multi-finger prehension: control of a redundant mechanical system *Progress in Motor Control* (pp. 597-618): Springer.

Olafsdottir, H., Zhang, W., Zatsiorsky, V. M. & Latash, M. L. (2007). Age-related changes in multifinger synergies in accurate moment of force production tasks. *Journal of Applied Physiology*, 102(4), 1490 -1501.

Park, J., Singh, T., Zatsiorsky, V. M. & Latash, M. L. (2012). Optimality versus variability: effect of fatigue in multi-finger redundant tasks. *Experimental Brain Research*, 216(4), 591-607.

Park, J., Sun, Y., Zatsiorsky, V. M. & Latash, M. L. (2011). Age-related changes in optimality and motor variability: an example of multi-finger redundant tasks. *Experimental Brain Research*, 212(1), 1-18.

Ranganathan, V. K., Siemionow, V., Sahgal, V. & Yue, G. H. (2001). Effects of aging on hand function. *Journal of the American Geriatrics Society*, 49(11), 1478-1484.

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(1), 45-58.

Scholz, J. P. & Schöner, G. (1999). The uncontrolled manifold concept: identifying control variables for a functional task. *Experimental Brain Research*, 126(3), 289-306.

Shim, J. K., Lay, B. S., Zatsiorsky, V. M. & Latash, M. L. (2004). Age-related changes in finger coordination in static prehension tasks. *Journal of Applied Physiology*, 97(1), 213-224.

Shim, J. K., Park, J., Kim, M. J. & KIm, S. J. (2011). Motor Variability and Synergy Research through Uncontrolled Manifold Analysis. *Journal of Korean Society of Sports Psycology*, 22(4), 127-142.

Shinohara, M., Scholz, J. P., Zatsiorsky, V. M. & Latash, M. L. (2004). Finger interaction during accurate multi-finger force production tasks in young and elderly persons. *Experimental Brain Research*, 156(3), 282 -292.

Tuller, B., Turvey, M. & Fitch, H. L. (1982). The Bernstein perspective: II. The concept of muscle linkage or coordinative structure. *Human Motor Behavior: An Introduction*, 253-270.

Turvey, M. T., Shaw, R. E. & Mace, W. (1978). Issues in the theory of action: Degrees of freedom, coordinative structures and coalitions. *Attention and Performance VII*, 557-595.

Voelcker-Rehage, C., Stronge, A. J. & Alberts, J. L. (2006). Age-related differences in working memory and force control under dual-task conditions. *Aging, Neuropsychology, and Cognition*, 13(3-4), 366-384.