TRAINING-SPECIFIC ADAPTATION OF MULTI-FINGER COORDINATION

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The purpose of the present study was to investigate the effects of finger Strength Training (ST) on multi-finger coordination as well as individual finger control, independence, and strength. Thirty-three healthy, young subjects were randomly assigned into four groups. Group 1 (G1) trained all fingers together, Group 2 (G2) trained individual fingers without restricting movements of the non-training fingers, and Group 3 (G3) trained individual fingers while restricting the movement of the non-training fingers. The control group (G0) did not undergo any training. All subjects in G1, G2, and G3 performed six sets of ten repetitions at 70% of their one repetition maximum for each sesson for six weeks, and there were three sessions of training per week. Identical experimental tests were conducted four times, biweekly, across the six-week training. Moment stabilizing multi-finger coordination increased only in G1, while force stabilizing coordination increased only in G3. Finger strength increased significantly in all training groups. Finger force control errors decreased significantly with ST for all the training groups. Finger independence also decreased significantly for all the training groups. We conclude that the neuromuscular adaptations to finger ST are specific to the training protocol being employed, yielding improvements in different types of multi-finger coordination (i.e., ST specificity for coordination), finger force control, finger strength and a decrease in finger independence. We suggest that ST protocol should be carefully designed for the improvement of specific coordination of multi-effector motor systems.

KEY WORDS: finger, coordination, training, specificity.

INTRODUCTION

The hand and fingers are one of the main tools the central nervous system (CNS) uses to physically interact with the external world. Multiple fingers are often used in everyday manipulative tasks, as simple as grasping a glass of water (Nowak & Hermsdorfer, 2003; Rearick *et al.*, 2003). For dexterous manipulation of an object, the CNS needs to control the kinetic redundancy caused by superfluous finger contact forces and moments of force (Shim *et al.*, 2003, 2005). Previous studies that investigated manipulative dexterity suggested a requirement for the CNS to *coordinate* the fingers for a stable performance during manipulative tasks, also known as multi-finger synergy. We define multi-finger coordination as the task-specific covariation of individual finger actions to stabilize a particular performance variable. When an intended finger moves or produces force voluntarily, other non-intendend fingers also move or produce forces involuntarily. This phenomenon has been known as finger “enslaving“. In this study, we tested whether the different training protocols, specifically designed to change the resultant force stabilizing coordination or the resultant moment stabilizing coordination, could induce the intended adaptations. Three hypotheses were tested. We hypothesized that the adaptation of multi-finger coordination would be specific to strength training protocols (Hypothesis 1). We hypothesized that finger independence would increase with the individual finger training without movements of non-training fingers (Hypothesis 2). Finally, we hypothesized that finger ST would increase finger strength and force control (Hypothesis 3).

METHOD

Data Collection

Subjects: Thirty-three young, healthy right handed subjects were recruited for the study. The subjects were assigned into four groups, each group with different training protocols. Group 1 (G1: n = 7) experienced simultaneous strength training of all four fingers. Group 2 (G2: n = 8) trained individual fingers without restriction to non-training finger movements. Group 3 (G3: n = 10) trained individual fingers with voluntary restriction to non-training finger movements (i.e.,

subjects tried not to move non-task fingers). The control group did not endure a training program (G0: n = 8).
Training and experimental procedure: All subjects performed 6 sets of 10 repetitions at 70% of their one repetition maximum (1-RM) for each session. Each repetition of finger training involved flexion and extension of all four fingers (G1) or single fingers (G2 & G3) about the metacarpophalangeal joints. There were three sessions of training per week. G3 subjects were asked to self restrict motions of the non-training fingers. For testing, all subjects sat in a chair facing a computer screen. The subjects were asked to rest the distal phalange of each finger in aluminum thimbles attached to force sensors. There were two main tests: maximal voluntary force (MVF) production and constant force production. Subjects performed five conditions for the isometric MVF test: four single-finger conditions and one four-finger condition using the right hand. For the constant force production test, a fixed horizontal line, which represented 20% of the four-finger MVF value for a particular subject, was shown on the computer screen as the force profile template. The actual force produced on the sensor by the subject was also shown on the computer screen as a different color for force feedback. The line representing the force feedback moved vertically upwards and downwards as the four-finger force increased and decreased, respectively. Subjects were asked to produce four-finger pressing forces to match the force profile template over a 10 s interval. The tests were conducted four times: before and after the six-week training and three times during the training.

Data Analysis

Uncontrolled Manifold (UCM) analysis: For the quantification of resultant force and resultant moment stabilizing coordinations, we used the framework of the uncontrolled manifold (UCM) analysis (Latash *et al.*, 2001; Schöner, 1995). According to UCM analysis, positive values of ΔV correspond to greater V_{UCM} (i.e., variability that does not cause performance error, "good" variability) than V_{ORT} (i.e., variability that causes performance error, "bad" variability) reflecting the coordination between different fingers to stabilize a particular performance variable (e.g., resultant force or moment). ΔV was calculated for total force stabilization (ΔV_{force}) and total moment stabilization (ΔV_{moment}). Finger independence (FI): Finger independence (FI) was calculated by subtracting the averaged value of non-intended finger forces (e.g., middle, ring, and little fingers) from 100% during intended finger MVF tasks (e.g., index finger). Constant error (CE): The absolute difference between the time trajectory of the four-finger total force and target force during the constant force production task was calculated. Maximal voluntary force (MVF): Finger strength was measured by the peak magnitude of four-finger force during MVF tasks.

RESULTS

Multi-finger coordination: ΔV_{force} increased significantly with training in G3, while it remained unchanged in G0, G1, or G2 (Fig. 1). The increases became more pronounced with the training progress. These findings were supported by two-way ANOVA which showed a significant GROUP x SESSION interaction [F(9,87) = 3.1, P < 0.01], GROUP effect [F(3,29) = 132.0, P < 0.001], and SESSION effect [F(3,87) = 5.2, P < 0.01]. On the other hand, ΔV_{moment} increased significantly with training in G1, while it remained unchanged in other groups. A significant increase of ΔV_{moment} in G1 was already observed after two weeks of training and the increase became larger after four and six weeks, thus indicating better moment stabilizing coordination with training. The increase became more pronounced after six weeks. These findings were supported by two-way ANOVA which showed a significant GROUP x SESSION interaction [F(9,87) = 3.1, P < 0.01], GROUP effect [F(3,29) = 132.0, P < 0.001], and SESSION effect [F(3,87) = 5.2, P = 0.01]. The significant improvements in ΔV_{force} only for G3 and in ΔV_{moment} only for G1 support Hypothesis 1 (i.e., resultant force stabilzing coordination and resultant moment coordination improve with four-finger and individual finger training, respectively).

Finger independence (FI): All training groups (G1, G2, and G3) showed significant decreases in FI after six weeks of training. The significant decrease in FI was observed after two weeks of training in G1 and G3, whereas, significant reductions were not observed until four weeks in G2. Moreover, the decrease of FI in G1 was significantly greater than those in G2 and G3. After the six weeks of training, FI of G1, G2, and G3 decreased to 85%, 93%, and 91%, respectively, of baseline (S0) FI values for each group. These findings were supported by two-way ANOVA, which showed a significant SESSION effect [F(3,87) = 136.4, $P < 0.001$], GROUP effect [F(3,29) = 3.5, $P < 0.05$], and GROUP x SESSION interaction [F(9,87) = 10.4, $P < 0.001$]. The decrease in FI in G3 with training does not support Hypothesis 2.

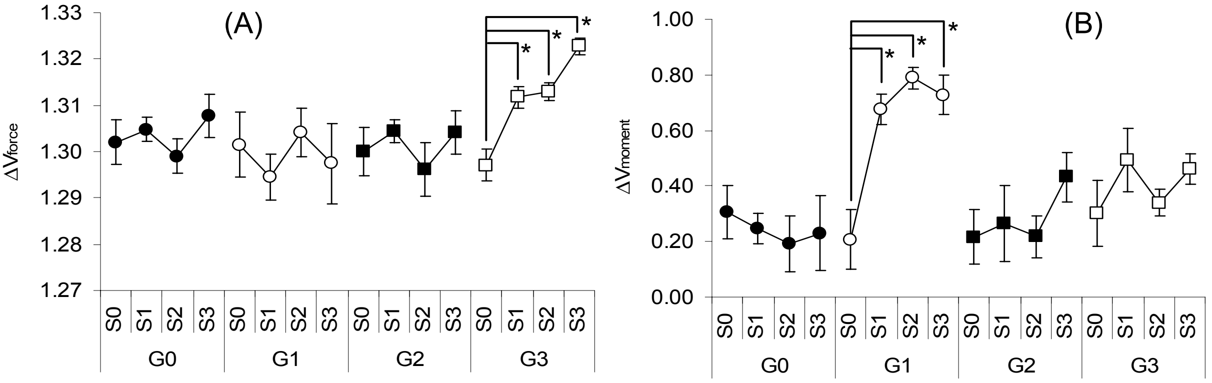

Fig. 1. (A) ΔV_{force} and (B) ΔV_{moment} during all finger pressing tasks. G0, G1, G2, G3 represent the control group, the group of four-finger simultaneous training, the group of individual finger training without restriction, and the group of individual finger training with self-restriction to non-training finger movements, respectively. S0, S1, S2, and S3 represent consecutive test sessions with two-week intervals. * signifies significant ($P<.05$) differences of ΔV between sessions.

Constant errors (CE): All training groups (G1, G2, and G3) showed a significant decrease in finger CE after six weeks of training (all $P < 0.05$). The significant decrease in CE was first observed after two weeks of training in G3, whereas, this was not observed until four weeks of training in G1 and G2. After four weeks, CE in G1, G2, and G3 decreased to 74%, 71%, and 66%, respectively, of the baseline session (S0) CE values for each group. These findings were supported by two-way ANOVA with significant SESSION effect [F(3,87) = 130.4, $P < 0.001$] and GROUP x SESSION interaction [F(9,87) = 9.5, $P < 0.001$]. The results suport Hypothesis 3.

Finger Strength: All training groups (G1, G2, and G3) increased MVF significantly with training (all $P < 0.05$), while MVF remained constant in the control group (G0). The earliest observed significant increases from baseline MVF were after four weeks of training in G1 and G3 and after six weeks in G2. When all groups were combined for calcualtion, MVF increased to 139% with training. These findings were supported by the significant SESSION effect [F(3,87) = 105.6, $P < 0.001$] and GROUP x SESSION interaction [F(9,87) = 11.9, $P < 0.001$]. The increases in MVF values with training support Hypothesis 3.

DISCUSSION

Increases in multi-finger coordination with coordination-specific training: The current study demonstrates that multi-finger coordination can be improved by coordination-specific ST protocols. The increases in ST-specific coordinations suggest that adaptations of the multi-finger neuromuscular system from regular resistance exercise are specific to the training protocols. The specific training protocols would yield independent changes to different multi-finger coordinations (e.g., specificity of training for multi-finger coordination). Our previous study shows that older adults have deficits in stabilizing the resultant moment of finger forces during grasping tasks (Shim et al., 2004). The results of the current study, showing moment stabilizing coordination with individual finger training, suggest that individual finger training would likely serve as a beneficial intervention for reversing these deficits in the elderly.

Changes in finger independence and inter-finger connection matrix with training: Humans are not capable of completely independent finger actions. Inter-finger connection matrix or enslaving matrix (i.e., a 4x4 matrix whose diagonal elements are task finger forces and other elements are non-task finger forces) has been used in previous studies to investigate kinetic interactions between fingers and the central nervous system control upon them (Danion et al., 2003; J. P. Scholz *et al.*, 2002; J. P. Scholz et al., 2003). The previous studies considered the enslaving matrix as a constant matrix. However, the current study showed that both the diagonal elements (i.e., finger strength) and non-diagonal elements (i.e., inter-finger connections) are plastic with training while demonstrating the increases of task finger forces (i.e., MVF increases) and the disproportionate increases of non-task finger forces (i.e., FI decreases).

Finger strength and performance: Previous studies have attributed strength gains with training to both neural adaptations of the CNS (e.g., changes in motor unit recruitment and firing frequency) and muscle morphological adaptations (e.g., changes in contractile elements and muscle architectures). However, neurological adaptations are more pronounced during the early stages of training (Kamen, 2004). The significant improvements in strength after only two weeks of training seems to indicate initial neurological, rather than morphological, adaptations. The increase in finger motor task performance with ST has been reported in several previous studies. The decrease in force errors can be considered an improvement to the performance of a multi-finger motor system for controlling finger force. Shinohara et al. (2003) proposed the “strength-dexterity trade-off hypothesis” by showing that finger independence decreases as strength increases. However, this assumption was based solely on the finger independence change with ST. The current study also observed a decrease in finger independence with an increase in finger strength. However, our finding that ST induces an increase in strength and force control performance (e.g., a decrease in CE and increase in multi-finger synergy) undermines the strength-dexterity trade-off hypothesis.

CONCLUSION

We conclude that the adaptations of neuromuscular system to multi-finger ST are specific to the training protocol being employed, yielding improvements in different types of multi-finger coordination (i.e., *coordination-specific ST*), finger force control, and finger strength as well as a decrease in finger independence. We suggest that ST protocol should be carefully designed for the improvement of specific coordination of multi-effector motor systems.

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