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Robotic finger perturbation training improves finger postural steadiness and hand dexterity

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ABSTRACT

The purpose of the study was to understand the effect of robotic finger perturbation training on steadiness in finger posture and hand dexterity in healthy young adults. A mobile robotic finger training system was designed to have the functions of high-speed mechanical response, two degrees of freedom, and adjustable loading amplitude and direction. Healthy young adults were assigned to one of the three groups: random perturbation training (RPT), constant force training (CFT), and control. Subjects in RPT and CFT performed steady posture training with their index finger using the robot in different modes: random force in RPT and constant force in CFT. After the 2-week intervention period, fluctuations of the index finger posture decreased only in RPT during steady position-matching tasks with an inertial load. Purdue pegboard test score improved also in RPT only. The relative change in finger postural fluctuations was negatively correlated with the relative change in the number of completed pegs in the pegboard test in RPT. The results indicate that finger posture training with random mechanical perturbations of varying amplitudes and directions of force is effective in improving finger postural steadiness and hand dexterity in healthy young adults.

1. Introduction

We perform fine hand-motor tasks in various types of activities, such as manipulating cloth buttons, playing musical instruments, and handling chopsticks. Whereas the hands are more dexterous than other parts of the body, normalized fluctuations in motor output during steady tasks are greater in the fingers compared with other parts of the limbs (Yoshitake and Shinohara, 2009). Steadiness of the motor output of the index finger and a measure of hand dexterity (i.e. pegboard test score) are positively associated (Kornatz et al., 2005; Marmon et al., 2011b) in older adults, while both are degraded with aging (Marmon et al., 2011b). Therefore, the development and examination of the strategies for improving the steadiness and dexterity with fingers are important for improving or maintaining the quality of life against aging and neuromotor impairments.

Motor training has been demonstrated to be efficacious in improving the steadiness of the index finger and hand dexterity. Resistance training using a heavy or light inertial load (Keen et al., 1994; Kornatz et al., 2005; Laidlaw et al., 1999) and functional task practice (Marmon et al., 2011a; Ranganathan et al., 2001) have improved the steadiness of the index finger in healthy older adults. Hand dexterity was also improved by resistance training using a light inertial load (Kornatz et al., 2005) and functional task practice (Marmon et al., 2011a; Ranganathan et al., 2001) in healthy older adults. It is possible that different types of training other than functional task practice or resistance training improve steadiness and hand dexterity. In principle, sensorimotor control and function can be improved or regained with trainings that can modulate not only motor output but also proprioception (conscious and unconscious sensations and integration). In upper-limb rehabilitation after wrist trauma (e.g. distal radius fractures, wrist ligament rupture), for example, exercises that aim to modulate proprioceptive function may be included such as: mirror therapy, blinded reproduction of passive joint angle, as well as reactive exercises against perturbations (Balan and Garcia-Elias, 2008; Hagert, 2010; Hincapie et al., 2016; Karagiannopoulos and Michlovitz, 2016). A training that stimulates proprioceptive function of fingers may thus lead to an improvement of finger steadiness and hand dexterity.

In the current study, development of unique perturbation training

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system for a finger was inspired by slackline training and handheld gyroscope/ Power ball exercise, which can improve whole-body postural control (Santos et al., 2016) and wrist motor function (Balan and Garcia-Elias, 2008; Hagert, 2010; Karagiannopoulos and Michlovitz, 2016), respectively. Slackline training is an emerging exercise in which an elastic polyester rope is stretched between two anchor points, on which a person stands and attempts to balance. This training involves unexpected perturbations due to the stretches of the rope, against which the person tries to maintain the control of balance. Handheld gyroscope/ Power ball exercise generates perturbing centrifugal forces in various directions, to which the forearm muscles can react unconsciously (Balan and Garcia-Elias, 2008; Hagert, 2010; Karagiannopoulos and Michlovitz, 2016). Therefore, this training also involves perturbations as in the case of slackline training. Interestingly, an improvement of postural control after the slackline training was accompanied by a reduction of H-reflex in the soleus (Keller et al., 2012). In a similar line, our previous works with vibration interventions demonstrated that a reduction of stretch reflex improves steadiness in the ankle (Yoshitake et al., 2004) and an enhancement of stretch reflex degrades steadiness in the index finger (Shinohara et al., 2005b). While the number of muscle spindles is less in hand muscles than leg muscles, the relative abundance of spindles (i.e. number of muscle spindles relative to muscle mass) in hand muscles is similar or greater compared with leg muscles (Banks, 2006). Thus, it is possible that a perturbation training of the index finger may improve finger postural steadiness and lead to an improved hand dexterity due to potential modulations of Ia afferent circuit. Since no device is commercially available that allows for such perturbation training for a finger, the efficacy of such training for steadiness and dexterity is unknown in older or young adults.

We thus decided to develop a robotic device for finger perturbation training with a vision of applying it to aged individuals as well as individuals with neuromotor impairment. Before applying this new training system to such populations, it is necessary to examine its feasibility and effects in healthy young adults for establishing a proof of concept and for enabling future comparison with other populations. We hypothesized that perturbation training of the index finger improves steady control of the finger and hand dexterity in healthy young adults. The purpose of this study was to understand the effect of robotic finger perturbation training on steadiness in finger posture and hand dexterity in healthy young adults.

2. Methods

2.1. Robotic finger training system

For examining the effect of perturbation training, we developed a robotic finger training system (RFTS) that provides rapid mechanical perturbations to a finger randomly in various amplitudes and directions (Fig. 1A). RFTS is designed to have the following functions: high-speed mechanical response, two degrees of freedom (DoF), and adjustable loading amplitude and direction. The base frame is made from aluminum-alloy extruded material (HFSB5, Misumi, Tokyo, Japan). Users place their forearm on an arm holder (11 × 8 × 6 cm) and grasp a hand holder (13 × 13 × 4 cm) with their middle, ring, and little fingers. The index finger of the users is attached to a finger holder at the proximal interphalangeal joint (Fig. 1B). The arm, hand, and finger holders are made from ABS (acrylonitrile butadiene styrene) resin using a 3D printer (FORTUS 250mc, Stratasys, Eden Prairie, MN, USA). Two finger holders (diameter of a finger ring: 1.3 and 1.7 cm) are made to accommodate the finger of most Japanese adults. The finger holder is driven by four brushed DC motors (DCX35L, Maxon Motor, Sachseln, Switzerland) through four fishing lines (Ultra dyneema WX8 #3, YGK, Tokushima, Japan) that are lightweight and non-ductile. RFTS is capable of applying forces from any directions in the *X-Y* (horizontal-vertical) plane. The maximum force capacity of RFTS is 16 N and 11 N in *X* (abduction/adduction) and *Y* (extension/flexion) directions, respectively. The range of motion of the finger folder of RFTS is ± 5 cm in both *X* and *Y* directions from the center of RFTS. The maximum velocity of driving the finger holder is 1.56 m/s. The torque and the position of each motor are controlled using a motor driver (ESCON, Maxon Motor, Sachseln, Switzerland). The system is powered by standard 100 V AC with an AC/DC converter (36 V) for the motors. With the mass of 3 kg and the dimension of 30 × 30 × 35 cm (in height × width × depth) for the platform, it is a mobile robotic system. RFTS can operate in the random-force mode and the constant-force mode as described in the following sections. The command for target force and position is sent from a personal computer using custom-made software (Simulink and xPCtarget, The Mathworks, Natick, MA, USA).

A) B)

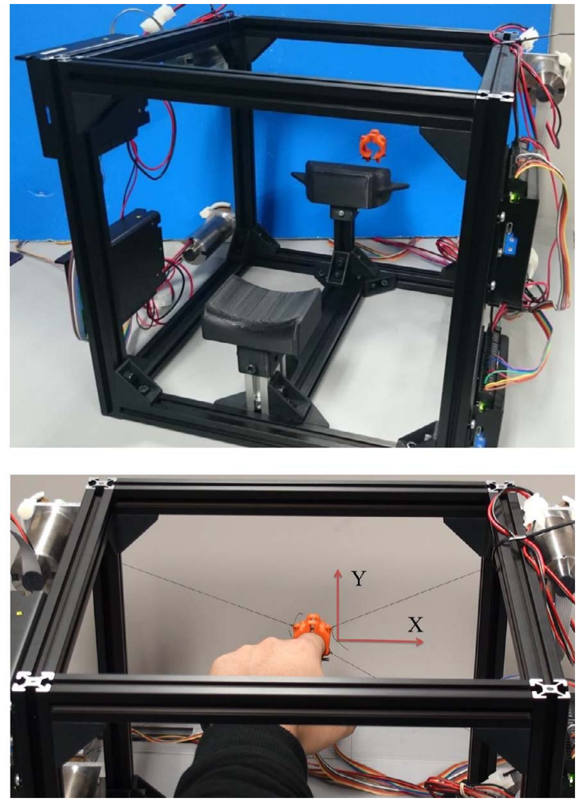

Fig. 1. (A) Platform of robotic finger training system (RFTS) that can apply forces from different directions at various timings via four brushed DC motors. (B) Top view of the experimental setup for training with the left index finger attached to RFTS. *X* and *Y* with arrows indicate the horizontal and vertical (i.e. finger abduction and extension) directions, respectively.

2.2. Human study

2.2.1. Subjects

A human study was performed to examine the efficacy of using RFTS for perturbation training in the random-force mode for improving steadiness of the index finger and hand dexterity. Forty-two healthy young adults (5 women and 37 men; age 26.7 ± 4.9 yr (mean ± SD); height 1.73 ± 0.07 m) were recruited. All subjects reported an absence of medical history of neuromuscular disorder and were right-hand dominant. Hand dominance was determined by self-report concerning the hand that is more frequently used for throwing and writing. The subjects gave written informed consent according to the procedures approved by the institutional ethics committee of the National Institute of Fitness and Sports in Kanoya.

Subjects were randomly assigned to one of the three groups: random perturbation training (RPT, $n = 14$), constant force training (CFT, $n = 14$), and control groups (CON, $n = 14$). In RPT and CFT, subjects performed postural control training with their index finger for 2 weeks