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Real time relationship between individual finger force and grip exertion on distal phalanges in linear force following tasks

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ABSTRACT

Individual finger force (FF) in a grip task is a vital concern in rehabilitation engineering and precise control of manipulators because disorders in any of the fingers will affect the stability or accuracy of the grip force (GF). To understand the functions of each finger in a dynamic grip exertion task, a GF following experiment with four individual fingers without thumb was designed. This study obtained four individual FFs from the distal phalanges with a cylindrical handle in dynamic GF following tasks. Ten healthy male subjects with similar hand sizes participated in the four-finger linear GF following tasks at different submaximal voluntary contraction (SMVC) levels. The total GF, individual FF, finger force contribution, and following error were subsequently calculated and analyzed. The statistics indicated the following: 1) the accuracy and stability of GF at low %MVC were significantly higher than those at high SMVC; 2) at low SMVC, the ability of the fingers to increase the GF was better than the ability to reduce it, but it was contrary at high SMVC; 3) when the target wave (TW) was changing, all four fingers strongly participated in the force exertion, but the participation of the little finger decreased significantly when TW remained stable; 4) the index finger and ring finger had a complementary relationship and played a vital role in the adjustment and control of GF. The middle finger and little finger had a minor influence on the force control and adjustment. In conclusion, each of the fingers had different functions in a GF following task. These findings can be used in the assessment of finger injury rehabilitation and for algorithms of precise control.

1. Introduction

Fingers are among the most complex and important body parts for accomplishing tasks in daily life and manufacturing as they consist of many joints and muscles. Grip is a primary hand movement that requires participation of all the fingers, and its accuracy and stability are of great interest in ergonomics, particularly in handle design and assessment (Pylatiuk et al., 2006; Harih and Dolšak, 2013; Rossi et al., 2014; Park et al., 2014; Shurrab et al., 2015). Finger injuries or disorders may cause difficulties in living and manufacturing. Understanding the mechanism of the individual finger's force and contribution during changing grip force (GF) will be of great help in rehabilitation engineering, precise control of manipulators, and other related fields.

For finger force (FF) distributions in static GF, current studies have shown that the middle finger (M) has the highest contribution in static grip trials and the little finger (L) has the lowest contribution (Ejeskär and Örtengren, 1981; Lee and Rim, 1990; Radhakrishnan and Nagaravindra, 1993; Kattel et al., 1996; Farris et al., 1997; Vigouroux et al., 2011; Kong et al., 2011; Rossi et al., 2012). The average contributions of M and L in former research are 32.5% and 14.1%, respectively (Kong et al., 2011). However, to date, there is no agreement in results on the contributions of the index finger (I) and ring finger (R) (Farris et al., 1997; Li, 2002; Aldien et al., 2005; Dumont et al., 2006; Lee et al., 2009; Rossi et al., 2012).

An acceptable explanation for this distribution of GF is from the difference in mass of the muscles related to the individual fingers (M has the largest mass fraction of muscle in the forearm, and L has the smallest) (Brand et al., 1981). However, this difference cannot explain the variance of contributions of I and R at different levels of submaximal maximum voluntary contraction (SMVC) (Kong et al., 2011).

The studies above tested individual FFs and contributions when GF was stable. For dynamic FF distribution, several studies of total FF followed a polyline as the target wave (TW) in order to investigate the distribution mechanism of the individual FFs (Li et al., 1998; Latash et al., 2001; Li and Leonard, 2006). Their studies were based on fingers pressing on a plate or board but not a grip on cylinder-shaped handles, which are widely used in rehabilitation engineering and industry.

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Most of the studies on cylinder handles were intended to determine the relationship between the cylinder diameter and stable SMVC of GF and discomfort (Kong and Lowe, 2005; Kong et al., 2007; McDowell et al., 2012; Kuo et al., 2013; Shurrab et al., 2015; Jarque-Bou et al., 2016). Few specialized on multi-finger force following grip task using a cylinder handle.

In rehabilitation of finger injuries, it is not enough to know the contribution of fingers in static grip. We need to examine the working conditions of each finger in a dynamic grip task. This will help to estimate the influence of single or multi-finger injuries and assess the rehabilitation procedure. In modern industry, there are tasks that operate manipulators to grasp some fragile objects, which require stable and accurate grasping force, for example, the operation of corrosive and radioactive reagents, or operation of explosive objects via remote control. In these cases, the movements of operating handles control the movements of the manipulator and the GF on handles controls the grasp strength. Understanding the mechanism of the individual FF exertion in a grip task may help provide an accurate force output.

In order to understand the dynamic relationship between fingers and GF when GF is changing, we designed a GF following experiment on a cylindrical handle. In the experiment, we obtained the individual FF from distal phalanges in the force following task to analyze the dynamic relationship between the individual FF, finger force contribution (FC), GF, and following error (FE) when GF follows the TW composed of line segments.

2. Methodology

2.1. Participants

Ten right-handed male subjects with similar hand sizes, reporting no history of upper limb injuries or musculoskeletal disorders, participated in the experiments. The mean and standard deviations (SD) of the participants' age, height, weight, hand length, and hand width were 27.5 (4.2) years, 175 (4.7) cm, 73.2 (10.2) kg, 19.2 (0.6) cm, and 8.9 (0.4) cm respectively.

2.2. Apparatus

A multi-finger GF measurement device (Fig. 1) was designed and constructed to obtain the individual and total FFs for this study. The cylindrical handle was 100 mm long to ensure a sufficient contact area

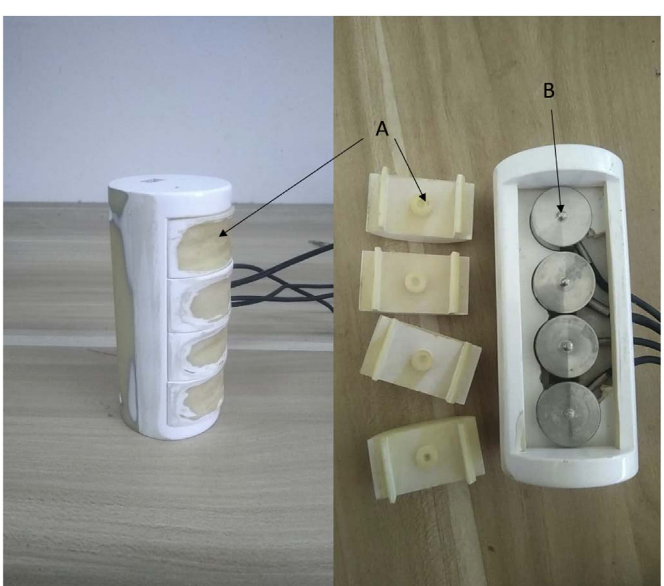

Fig. 1. Multi-finger force measurement device. A: Finger pads; B: Sensors.

between the hand and handle as neither of the participants' hand width reaches 100 mm. The diameter of the handle was 45 mm. The finger side consists of four independent finger pads with smooth grooves on each of them. The pad was 20 mm in width to provide an appropriate place for each finger (maximum width of fingertip in the power grip was between 14 mm (L) and 19 mm (M)). The force on either pad will not interfere with the load cells of other pads. The grooves were added to ensure that the fingers were stable in their position and did not slide. The grooves were 3 mm in depth, which yields an actual grip span of 42 mm.

Four HT-7303 M3-20 KG (Hangyudongfang High-tech Development Co. Ltd., Beijing, China) force sensors (ranging from 0–20 kg, 20 mm diameter, ± 0.5% FS) were used to obtain the individual FF with 700 Hz sampling rate. The load cell can record force data from vertical direction of the finger pads. The load cells were calibrated with standard weights before the experiment.

The software for the force-following task was custom-coded by C#. The functions of the software include design and display of the target force wave, display of total GF in the middle of the interface (60% of display area) and individual FF at the bottom in real time (60 Hz refresh rate), and start/stop and save buttons. All data acquired by the software were saved as.txt files and processed in MATLAB and SPSS.

2.3. Procedures

All participants were given informed consent approved by the ethical committee of the university before the experiment. The participants were subsequently provided with a brief introduction concerning the following procedure while undergoing exercises with the measuring system (TW for exercises were randomized straight lines or curves given by the experimenter). After preparation, the participants sat on a chair upright with shoulder hanging down to the side of the upper trunk. The elbow of the right arm was bent to 90° with an abduction of 45°, while the wrist remained in neutral position. The thumb was placed on the side of the handle to ensure that only the other four fingers participated in the trials during all tasks including the maximal voluntary contraction (MVC) trials.

The participants exerted MVC for 5 s two times, with a rest of 3 min (Lim and Kong, 2014). The highest values were recorded as MVC. The TWs were then calculated based on MVCs.

In the force following tasks, the participants were required to exert a GF to follow the TW displayed on the middle of the screen as close as possible and ignore the individual FF displayed at the bottom in two separate tasks for one time (low = 20%–40% MVC task and high = 60%–80% MVC task). The LOW MVC task was performed first to prevent fatigue. The HIGH MVC task was performed when the participant reported an adequate rest, which was no less than 3 min.

2.4. Data and statistics

The force following task is a 35 s trial in which the TW was a 30 s long polyline consisting of seven segments (Fig. 2).

The purpose is to investigate relationships of finger and GF while GF is changing. So TW should include increase part and decrease part separated by hold part. LOW is under 50% of MVC and HIGH is above it so 20% MVC is appropriate as changing area. As shown in Fig. 2, the TW in the trial (taking the LOW trial as an example) consists of seven segments depending on the time. A 5 s preparation time was set for the participants to reach the target force before the target line. After preparation, the trial begins with a 5 s polyline with a slope of 0 followed by a 5 s trial with a slope of 4% MVC/s, within which the MVC rises from 20% to 40%. This was followed by another 15–20 s stable trial, and in 20–25 s, the slope was −4% MVC/s. After another 5 s stable trial, a steeper slope of 8% MVC followed, which lasted 2.5 s. Next, the TW decreased with a slope of −8% MVC for 2.5 s.

The four sensors were placed on distal phalanges of each finger to