INTERACTIONS BETWEEN FINGERS DURING RAPID FORCE PULSE PRODUCTION

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

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Manual function is a key determinant of functional independence. It is well known that manual dexterity declines with aging and negatively impacts quality of life. Therefore, much work has focused on understanding the biomechanics and motor control of manual function in general, and the action of the fingers in particular. Previous research has revealed consistent patterns of interdependence in the action of the fingers that (1) alter with age, and (2) have consequences for manual control, and thereby manual function. Most of this previous work on finger behavior quantifies finger capacities and interactions in terms of maximal forces. However, activities of daily living likely require individuals to rapidly change forces more frequently than produce maximal forces. Therefore, the present work quantifies, for the first time, finger capacities and interactions during rapid increase and decrease in finger forces, and how these quantities change with age.

Young and older adults performed maximal force production tasks and also tasks that required them to rapidly increase or decrease finger forces from three initial force levels using multiple combinations of the fingers of their dominant hand. The maximal finger forces and force rates, and the interdependence of the fingers (enslaving, individuation, sharing, and deficit) during both behaviors are reported in detail. Overall, similarities in finger behavior patterns obtained from maximal force and maximal force rates were observed. However, some differences are also noted, and novel findings (especially, comparison between force increase and decrease) are reported. Finally, future work that may lead to clinical applications is discussed.

1. INTRODUCTION

1.1 Ballistic & Maximal Contractions

The ability to produce ballistic (i.e. rapidly changing) and maximal forces (without any time constraint) with the musculature are perhaps related, but different biomechanical abilities. Both these abilities are relevant to daily living. For example, to lift heavy groceries, people need to produce large forces in both the lower and upper extremities. However, in daily living, people likely produce force changes at rates close to their maximal possible physiological values more frequently than they exert physiologically possible maximal force. That is, maximal force rate abilities may be more functionally relevant compared to maximal force production abilities. For example, instead of trying to lift all the heavy groceries in one attempt with maximal force production, an individual may choose to lift smaller loads multiple times. In contrast, rapid manipulation will require rapid force changes, even when the magnitudes of the involved forces are small. Therefore, activities such as navigating a crowded street may require high force rates to rapidly change direction in response to a dynamic environment.

The importance and relevance of rapid force change ability can be gauged from its use in athletics. There, maximal force and maximal force rate are both used as measures of strength, and specialized training is used to improve either capability. For example, in a one repetition maximum (1RM) bench press, athletes reach full arm extension during the first repetition but would fail to reach full arm extension in the second repetition. Similarly, explosive strength (Kochanowicz et al., 2019; Freitas et al., 2018) and explosive power (Saeterbakken et al., 2018) are also measured. Explosive strength is the ability to generate force (or torque) as quickly as possible and is measured as the *rate of force development* (Kochanowicz et al., 2019). Explosive power is typically used to measure maximal anaerobic power and is typically measured on a cycle ergometer in the Wingate anaerobic test (WAnT) (Zupan et al., 2009; Saeterbakken et al., 2018; Gacesa, 2009). In both explosive strength and power measures, athletes perform movements with maximal effort as quickly as possible. Resistance or weight training and plyometrics are commonly used training techniques that focus on maximal strength and explosive strength, respectively.

Nevertheless, clinical assessments of strength tend to only focus on maximal force production. In the domain of manual function, which is the focus of this work, hand grip strength is used as one indicator of health. It is known that lower grip strength in middle age leads to functional limitations and disabilities later in life (Rantanen et al., 2014). Reduced hand grip strength has been associated with greater disabilities while performing activities of daily living such as walking, feeding oneself, dressing, cooking food, doing housework and mobility such as climbing stairs and carrying heavy objects (Giampaoli et al., 1999). With healthy aging, older adults also begin to perform manual tasks slower and less accurately than young adults and show a loss in manual dexterity starting around the age of 60 years (Kallman et al., 1990; Ranganathan et al., 2001). Furthermore, therapeutic interventions focus on improving maximal hand force. This is well supported by research showing that strength training improved manual function (Kornatz, 2005; Olafsdottir et al., 2008). However, in contrast to athletics, improving ballistic force production ability is seldom the focus of therapeutic interventions. It is likely that ballistic training will provide functional benefits over and above those obtained by traditional strength training.

It is difficult to argue for the inclusion of ballistic force training in clinical settings because the evidence indicating benefits from such a protocol does not exist. In fact, even the capabilities of the hand and the fingers for explosive force production have not been sufficiently documented. The scientific literature concentrates on the steadiness of sub-maximal finger forces (Enoka et al., 2003) or the maximal force of the fingers (Shinohara et al., 2003b; Zatsiorsky et al., 2000), with a few exceptions (Watanabe et al., 2011). However, a systematic exploration of force change ability in the fingers is lacking. The group of Zatsirosky et. al have provided extensive data describing the interactions between the fingers during maximal force production (Zatsiorsky et al., 2000; Zatsiorsky et al., 1998; Wilhelm et al., 2013), how these dependencies change with age (Shinohara et al., 2004), and how these dependencies may influence the control of the hand during object manipulation. The goal of the present work is to extend the work of Zatsiorsky et. al by quantifying (1) the maximal force rate abilities of the fingers, (2) the interdependence of the fingers during the production of rapid force changes, and (3) the influence of aging on these variables. In this study, young and older participants will produce rapid increases and decreases in the finger forces in isometric conditions with their dominant hand. The primary outcome measure is the peak force rate produced by the fingers. To characterize finger dependencies, participants performed the tasks with various finger combinations. Since this is the first time such measurements are being conducted, we hypothesize that the patterns of interdependence obtained from maximal force rates will resemble those observed during maximal force production tasks.

It is well known that manual dexterity declines with healthy aging starting at the age of 60 years (Desrosiers et al., 1999; Cole et al., 2010), results in reduced ability to perform many activities of daily living (hygiene, dressing, etc.), and negatively impacts the quality of life (Jette et al., 1990; Incel et al., 2009). The data obtained from this study will address the gap in the literature regarding the capacity to produce ballistic forces with the fingers. Maximal finger forces reduce with age (Shinohara et al., 2004; Shinohara et al., 2003a). Therefore, we predict that the maximal force rates will also reduce with age.

We varied the initial force with respect to which the rapid changes in force will be executed. Different initial forces in the fingers means that the current muscular activation and the stiffness of the musculo-tendinous units will be different. Muscle activation dynamics are often described as first-order system, where the rate of activation change is proportional to the current activation level (Thelen, 2003; Winters, 1995). The tendon stiffness changes in a non-linear fashion for low forces. Beyond this *toe region*, the stiffness is constant (Zajac, 1989). A stiffer tendon will transmit muscle contractile force more efficiently to the effector, since a smaller component of the contractile energy is expended in stretching the tendon itself. Therefore, the initial force will likely alter the peak force rate measured in this experiment.

Finally, we also explored rapid force increases and decreases from the initial force. It is well known that muscles can contract faster than they can relax (Zajac, 1989). Muscle relaxation depends on the re-uptake of calcium ions into the sarcoplasmic reticulum, which is a slower process than the calcium ion release. Therefore, the rate of muscle force decline can be much slower than the rate of muscle force development. In slow accurate production of force generation and force reduction, firing rates of motor units at the same force level are slower during force relaxation than force generation. Furthermore, the motor cortex is less active during force relaxation than force generation, and there is reduced accuracy during force relaxation at lower initial forces than force generation (de Luca et al., 1982; Denier van der Gon et al., 1985; Spraker et al., 2009; Ohtaka and Fujiwara, 2016). Based on these considerations, we decided to explore peak force increase and peak force decrease from various initial force values.

2. METHODS

2.1 Participants

Nine young adults (4 female, 25.8 ± 4.4 years, 17.5 ± 1.0 cm hand length [distal wrist crease to tip of middle finger], 7.9 ± 0.3 cm hand width [MCP joint of first to last digit]) and ten older adults (3 female, 71.6 ± 8.8 yrs, 18.9 ± 1.4 cm hand length, 8.6 ± 0.8 cm hand width) were recruited from Purdue University and local senior living communities. Exclusion criteria included any neuro-muscular diseases, previous hand injuries, or existing upper limb discomfort (self-report). Participants were right-handed based on their preference in daily tasks such as eating and writing. All participants signed an informed consent approved by the Purdue University Institutional Review Board.

2.2 Apparatus

Four force transducers (Nano 17, ATI Industrial Automation Inc., Apex, NC) were used to measure force production by the fingertips. The sensors were calibrated before each data collection session to exclude the weight of the fingertips from the force readings. A digital web camera (720p HD LifeCam Cinema, Microsoft Co., Albuquerque, NM) recorded the fingertips on the sensors. Three smooth objects made out of an epoxy wood replacement compound (WoodEpox, Abatron Inc., Kenosha, WI) were molded to hands of different sizes and then painted with paint primer. One of the three smooth objects, best suited to the hand size of the participant, was placed underneath the palm to maintain a consistent hand configuration throughout the experiment (Figure 2.1).

2.3 Experimental Setup

Participants sat at a table and faced a computer monitor (53.34 cm x 33.02 cm), approximately 0.8m away, that provided visual feedback of the finger forces. To minimize the movement of the arm over the course of the experiment, the right forearm was strapped to a wooden platform with Velcro while the fingertips rested on four transducers. The force transducers were also fixed to this wooden platform. A smooth object was placed underneath the palm of the right hand and secured to the wooden platform with Velcro. Each sensor was adjusted along the anterior-posterior direction to the length of individual fingers and then fixed in position (Figure 2.1). For each participant, the sensor configuration was recorded and was identical throughout the experiment. The web camera was placed 5 cm from the top of the wooden

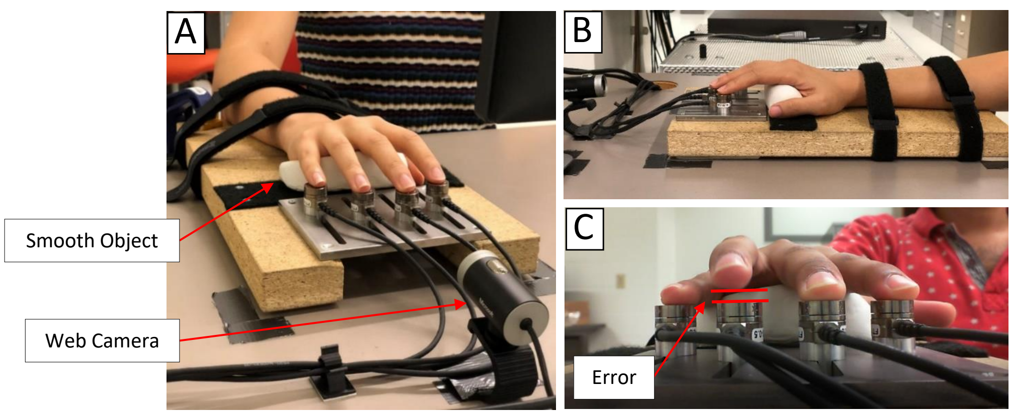


Fig. 2.1: Front view (A), side view (B), and web camera view (C) of the experimental setup. The web camera was used to observe errors and a smooth object was placed under the hand to maintain a consistent hand configuration.

board and was used to capture errors (i.e., if fingertips lifted off sensors) during the experiment (Fig. 2.1C).

The proximal interphalangeal joints of the fingers were at approximately 35 degrees flexion while the metacarpophalangeal joints were at approximately 20 degrees flexion. The shoulder was abducted and flexed at approximately 45 degrees, and the elbow joint was flexed at approximately 90 degrees. During the experiment, the left forearm rested on top of the table. The location of the wooden platform, computer monitor, and web camera was fixed for all participants.

2.4 Procedure

Both young and older adult participants performed three types of isometric finger-force production tasks. The first task measured the maximal voluntary contraction (MVC) of the fingers in which participants pressed with maximum exertion on the force sensors. Next, the up pulse task measured rapid increases in force in which participants produced a rapid increase in force. The down pulse measured rapid decreases in force in which participants reduced the force on the sensors without losing contact between the fingers and sensors. Participants generated these rapid increases and decreases in force from three initial forces.

2.4.1 Finger Conditions

All experimental tasks were performed with four fingers in contact with the sensors. However, for each trial, the experimenter specified the fingers that would be used to produce force. These fingers are called 'master fingers'. The uninvolved fingers are called the 'enslaved fingers'. Young adult participants performed each task with the following 15 master finger conditions: I (index), M (middle), R (ring), L (little), IM, IR, IL, MR, ML, RL, IMR, IML, IRL, MRL, and IMRL (all four fingers concurrently). The number of master finger conditions was reduced for the older adults to minimize the potential of fatigue in the fingers. The older adults performed each task with the following 5 master finger conditions: I, M, R, L, and IMRL. For all participants, the order of master finger conditions were randomized. For each trial in the experiment, errors were identified visually by an experimenter referred to as a "spotter". If the spotter reported an error during a trial, the participant repeated the same trial after a 20s break for the young adults or a 30s break for the older adults.

2.4.2 Maximum Voluntary Contraction Task

In the first task, participants pressed down on the sensors with specific master fingers with maximal effort for 6s. The total force produced by the master finger(s) (sum of vertical forces; $F_T = \sum F_i$) was displayed on the computer screen as a 'x' cursor. Participants performed two maximum voluntary contraction (MVC) trials for each master finger condition. The young adult participants performed 30 MVC trials with a 20s break in between each trial. The older adult participants performed 10 MVC trials with a 30s break in between each trial. For each master finger condition, the highest total force was recorded as the MVC for that finger condition. The initial force values for the pulse tasks described below were set at 10%, 25%, and 40% of the participants' MVC values for each master finger condition.

2.4.3 Down Pulse Task

In the down pulse task, participants generated a rapid decrease in force from three initial forces set at 10%, 25%, and 40% of the MVC for every finger condition. For example, if a participant produced a MVC value of 46 N for the IMRL finger condition, then the three initial forces for the down pulse task were 4.6 N, 11.5 N, and 18.4 N for the IMRL trials. Similarly, if a participant produced a MVC value of 30 N with the index finger, then the initial forces for the down pulse task with the index finger were 3.0 N, 7.5 N, and 12 N. Young adult participants performed the down pulse task with 15 finger combinations and older adults participants performed the task with 5 finger combinations.

In addition to feedback on the total force, a stationary box, which indicated the initial force level, was displayed on the computer screen. At the start of each trial, participants modulated the total force of the master fingers and moved the 'x' into the target force box. After the 'x' stabilized within the box for approximately 3s, the verbal cue "relax" was given and participants relaxed the master fingers as fast as possible to a resting state without errors (i.e., without lifting any of the fingers from the sensors). The fingers remained in their resting state until the end of the trial. The participants were informed that this was not a reaction time task and that they should choose the moment to begin the force change voluntarily after the cue. Participants performed all master finger conditions for the same initial force (initial force block) before moving on to the next initial force. Participants performed two trials (10s each) for each master finger condition. Therefore, young adult participants performed 90 down pulse trials with a 20s break in between trials and older adult participants performed 30 down pulse trials with a 30s break in between trials. All participants had practice trials prior to the pulse tasks.

2.4.4 Up Pulse Task

In the up pulse task, participants generated a rapid increase in force from the same three initial forces as the down pulse trials. At the beginning of each trial, participants moved the 'x' into the box. After the 'x' stabilized within the box for approximately 3s, the verbal cue "go" was given and participants pressed on the sensors as hard and fast as possible. Then all fingers relaxed to a resting state for the remainder of the trial. Similar to the down pulse task, this was not a reaction time task because the participant produced a rapid force change at a self-selected instant after the experimenter's cue. The duration of trials, number of trials, and the amount of rest was the same as the down pulse trials. All participants had practice trials prior to the pulse tasks.

2.4.5 Experimental Sessions

Young adult participants performed the experiment in two separate sessions (1.5 hours each). Both sessions occurred within 7 days with at least one day of rest in between sessions. In their first session, young adult participants first performed the MVC task and the majority of the down pulse task (approximately two initial force blocks). In the second session, the young adult participants performed the rest of the down pulse task followed by the up pulse task. Older adult participants completed the experiment in one session (2.5 hours). The MVC task was performed first but the order of the down and up pulse task was randomized. Additionally, the older adult participants repeated the MVC task at the end of the experiment (see Table 1 and 2 in the Appendix).

Several precautions were taken to minimize fatigue. Young adult participants performed the experiment in two sessions. Between each trial there was a 20s break. There was approximately a 8 minute break between the initial force blocks within the up and down pulse task and between the tasks (transition between MVC, down pulse, and up pulse). Each young adult participant spent about 33 minutes producing force and 85 minutes resting (excluding the rest between the two sessions; see Table 1 in the Appendix for further details). The young adults always performed the down pulse in the first session since after the maximal exertion of the fingers in the MVC task, the down pulse task would likely result in less fatigue than the up pulse.

Generally, older adults feel more fatigue. This is supported by self-report as well as empirical work. For example, in a longitudinal study, older adults self-reported a general fatigue of 29% at the age of 70 and then reported a fatigue of 68% at the age of 85 (Moreh et al., 2010). Furthermore, older adults show a larger power deficit compared to young adults when subjected to the same fatigue protocol (Power et al., 2012). We accounted for the potential higher fatigue in older adults by reducing the number of finger conditions from fifteen to five. Consistent with previous literature on finger force production studies, older adults performed all tasks with the conditions I, M, R, L, and IMRL (Shinohara et al., 2003a; Shinohara et al., 2004; Oliveira et al., 2008; Kapur et al., 2010).

Older adults performed the experiment in one session with a 30s break between trials. There was approximately a 8 minute break between the initial force blocks within the up and down pulse task and between the tasks. Each older adult participant spent about 14 minutes producing force and 90 minutes resting (see Table 2 in the Appendix for further details). After the pulse tasks, the older adult participants repeated the MVC task to determine if fatigue occurred. All participants were encouraged to ask for additional rest if they felt fatigue. However, none of the participants asked for additional rest.

The experimental protocol for the young and older adults is described below in Table 2.1.

Table 2.1: Summary of the differences in the protocol for the young and the older adults. For a detailed outline of experimental sessions see Appendix Table 1 and 2.

Protocol	YA	OA
Number of finger conditions	15	5
Number of MVC trials	30	10
Initial forces	10%, 25%, 40%	10%, 25%, 40%
Number of down pulse trials	90 (15 x 3 x 2)	30 (5 x 3 x 2)
Number of up pulse trials	90 (15 x 3 x 2)	30 (5 x 3 x 2)
Rest between trials	20s	30s
Sessions	2 x 1.5 hrs	1 x 2.5 hrs
Task duration/Rest duration	33 mins/85 mins	14 mins/90 mins

2.5 Video Coding

The video recordings from the web camera were saved. After data collection, the video recordings were reviewed by two people referred to as "coders." The coders identified any errors (i.e., fingertips lost contact with the sensors) the spotter missed or misjudged during the experiment. For every trial, coders independently determined if an error had occurred. Inter-rater reliability between coders was calculated for 100% of all trials for young and older adult participants using Cohen's kappa (κ) (Landis and Koch, 1977). For the young adult population, there was moderate agreement between coders (κ = 0.61, $p<0.01$). For the older adult population, there was substantial agreement between coders (κ = 0.80, $p<0.01$).

After inter-rater reliability was assessed, trials that were scored differently between coders were reviewed. Coders disagreed on 119 trials out of 2009 total trials (6%) for the younger adults and on 55 trials out of 941 total trials (6%) for the older adults. Coders reviewed these trials together and came to an agreement if the trials were successful or had an error. All trials with an error were removed for data analysis. For young adults, 142 error trials out of 2009 total trials were removed (7.1 %) and for older adults 170 error trials out of 941 total trials (18.1%) were removed.

2.6 Data Analysis

Analog signals of the normal force for each sensor were collected by The Motion Monitor system (Innovative Sports Training, Inc., Chicago, IL) and sampled at 1000 Hz. These force readings were exported into a custom Matlab program (MATLAB 9.2, The Mathworks Inc., Natick, MA) and were low-pass filtered at a cutoff frequency of 10 Hz using a fourth-order, zero-lag Butterworth filter.

2.6.1 Maximum Voluntary Contraction Task

For each finger condition, participants performed two MVC trials. Out of two trials, the trial with the highest total force value was recorded as the MVC and used to determine the initial forces during the experiment and was also used in the analysis. However, if this MVC trial had an error as determined by the coders, then the second trial was used used to determine the MVC. If the difference between the second trial and the original MVC trial was more than 5 N, then the pulse trials were removed from the analysis (68 out of 3018 trials were rejected due to this issue).

For each MVC trial, the force produced by each finger was measured at the instant when the total force reached the peak value. Therefore, young adult participants had four force values for 15 different master finger conditions and older adult participants had four force values for 5 different master finger conditions. These force values were used to compute *force enslaving*, *force individuation index*, *force deficit*, and *force sharing*. In previous literature, these computations have been used to assess the interactions between fingers during isometric maximal force production (Kilbreath and Gandevia, 1994; Li et al., 1998; Zatsiorsky et al., 1998; Zatsiorsky et al., 2000; Shinohara et al., 2003a). We performed the same computations to determine how the maximal force production of the young and older adult participants in our study compare to previous results.

Force enslaving is the involuntary force production by the non-instructed "enslaved" fingers when single or multiple master fingers produce maximal force. Force enslaving is computed for all master finger conditions except for the IMRL condition since, in this condition, there are no enslaved fingers. Force enslaving is the ratio of the force produced by a finger when it is enslaved to the force produced by the same finger when it is the only master finger, expressed as a percentage (Kilbreath and Gandevia, 1994; Zatsiorsky et al., 1998). It is given by:

$$E_{i,j} = 100 \times \frac{F_{i,j}}{F_{i,i}}, \tag{2.1}$$

where i = enslaved finger (I, M, R, L) and j = master finger(s). For the young adults, this yields a matrix of enslaving values as depicted in Table 2.2. For the older adults, this yields a matrix of enslaving values as depicted by the first four master finger conditions in Table 2.2. The top four rows of Table 2.2 are used to compute the *average enslaving* for each finger by computing the average of the non-diagonal elements in each column (blue cells in Table 2.2; Shinohara et al., 2003). For example, the average force enslaving for the index finger is the average of $E_{I,M}$, $E_{I,R}$, and $E_{I,L}$

and the average force enslaving for the ring finger is the average of $E_{R,I}, E_{R,M}$, and $E_{R,L}$.

The *force individuation index* is the maximal force production of the master fingers if the enslaved fingers did not produce any force (Häger-Ross and Schieber, 2018). The force individuation index is obtained from the average of the enslaving values of the non-diagonal terms in each row (gray cells in Table 2.2). For example, the average force individuation index for the index finger is the average of $E_{M,I}, E_{R,I}$, and $E_{L,I}$ and the average force individuation index for the ring finger is the average of $E_{I,R}, E_{M,R}$, and $E_{L,R}$. The individuation index was computed for each finger using the formula:

$$I_j = 100 - (\frac{1}{3}\sum_{i=1}^{3} E_{i,j}). \tag{2.2}$$

Force deficit is the difference between the force produced by a master finger in a single finger condition and the force produced by the same finger in the IMRL condition (Zatsiorsky et al., 2000; Shinohara et al., 2003a). A finger typically produces greater force in its single finger condition compared to the IMRL finger condition. This reduction in force production between conditions is defined as force deficit. This difference was divided by the force produced by the master finger in its single finger condition and expressed as a percentage. Therefore, the force deficit is given by:

$$D_j = 100 \times \frac{F_j - F_{j,IMRL}}{F_j}. \tag{2.3}$$

Force sharing is the ratio of the force produced by a master finger in the IMRL condition to the total force in the IMRL condition, expressed as a percentage (Li et al., 1998; Shinohara et al., 2003a). It is given by:

$$S_j = 100 \times \frac{F_{j,\ IMRL}}{\sum_{j=1}^{4} F_{j,\ IMRL}}. \tag{2.4}$$

Table 2.2: Representative enslaving matrix for young adults. The first 4 rows represents the measurements obtained for the older adults. The force enslaving is the average of the non-diagonal elements in each column in the first four rows of this table (e.g., the blue cells) and the force individuation index is obtained by averaging the non-diagonal elements in each of the first four rows (e.g., the gray cells).

	Enslaved Fingers			
Master Fingers	Index	Middle	Ring	Little
I	$\mathbf{E_{I,I}}$	$E_{M,I}$	$E_{R,I}$	$E_{L,I}$
M	$E_{I,M}$	$\mathbf{E_{M,M}}$	$F_{E,M}$	$E_{L,M}$
R	$E_{I,R}$	$E_{M,R}$	$\mathbf{E_{R,R}}$	$E_{L,R}$
L	$E_{I,L}$	$E_{M,L}$	$E_{R,L}$	$\mathbf{E_{L,L}}$
IM	$\mathbf{E_{I,IM}}$	$\mathbf{E_{M,IM}}$	$E_{R,IM}$	$E_{L,IM}$
IR	$\mathbf{E_{I,IR}}$	$E_{M,IR}$	$\mathbf{E_{R,IR}}$	$E_{L,IR}$
IL	$\mathbf{E_{I,IL}}$	$E_{M,IL}$	$E_{R,IL}$	$\mathbf{E_{L,IL}}$
MR	$E_{I,MR}$	$\mathbf{E_{M,MR}}$	$\mathbf{E_{R,MR}}$	$E_{L,MR}$
ML	$E_{I,ML}$	$\mathbf{E_{M,ML}}$	$E_{R,ML}$	$\mathbf{E_{L,ML}}$
RL	$E_{I,RL}$	$E_{M,RL}$	$\mathbf{E_{R,RL}}$	$\mathbf{E_{L,RL}}$
IMR	$\mathbf{E_{I,IMR}}$	$\mathbf{E_{M,IMR}}$	$\mathbf{E_{R,IMR}}$	$E_{L,IMR}$
IML	$\mathbf{E_{I,IML}}$	$\mathbf{E_{M,IML}}$	$E_{R,IML}$	$\mathbf{E_{L,IML}}$
IRL	$\mathbf{E_{I,IRL}}$	$E_{M,IRL}$	$\mathbf{E_{R,IRL}}$	$\mathbf{E_{L,IRL}}$
MRL	$E_{I,MRL}$	$\mathbf{E_{M,MRL}}$	$\mathbf{E_{R,MRL}}$	$\mathbf{E_{L,MRL}}$

2.6.2 Force-Rate

The novel contribution of this work is the quantification of the interaction between the fingers during rapid changes in finger forces. This was achieved with the measurement and computation of the same indexes of finger dependence but with maximal force-rates rather than maximal forces. Rapid force production of the fingers is measured by the maximal rate of force change. Therefore, for all the down and up pulse trials within a given master finger condition, the first derivative of the total force time curve was computed to obtain a total force-rate time curve. The force-rate time curve for each individual finger force was also computed. The peak of the total force-rate time curve was located. At this time coordinate, the force-rate produced by each finger was measured (Figure 2.2). The total force-rate and the force-rate produced by each finger was averaged across repetitions and used for further computations.

For both the down and up pulse task and for each initial force condition, young adult participants had four force-rate values (N/s) for 15 different master finger conditions and older adult participants had four force-rate values (N/s) for 5 different master finger conditions. These force-rate values were used to compute *maximum force-rate (MFR)*, *force-rate enslaving*, *force-rate individuation index*, *force-rate deficit*, and *force-rate sharing* separately for the down and up pulses, and the initial force values. These are computed the same way as described in section 1.6 but with force-rates as the inputs instead of forces (see Equations 2.5, 2.6, 2.7, & 2.8). Note that the force rates for the down pulses are multiplied by -1, so that the magnitudes of the rates can be compared across pulse types.

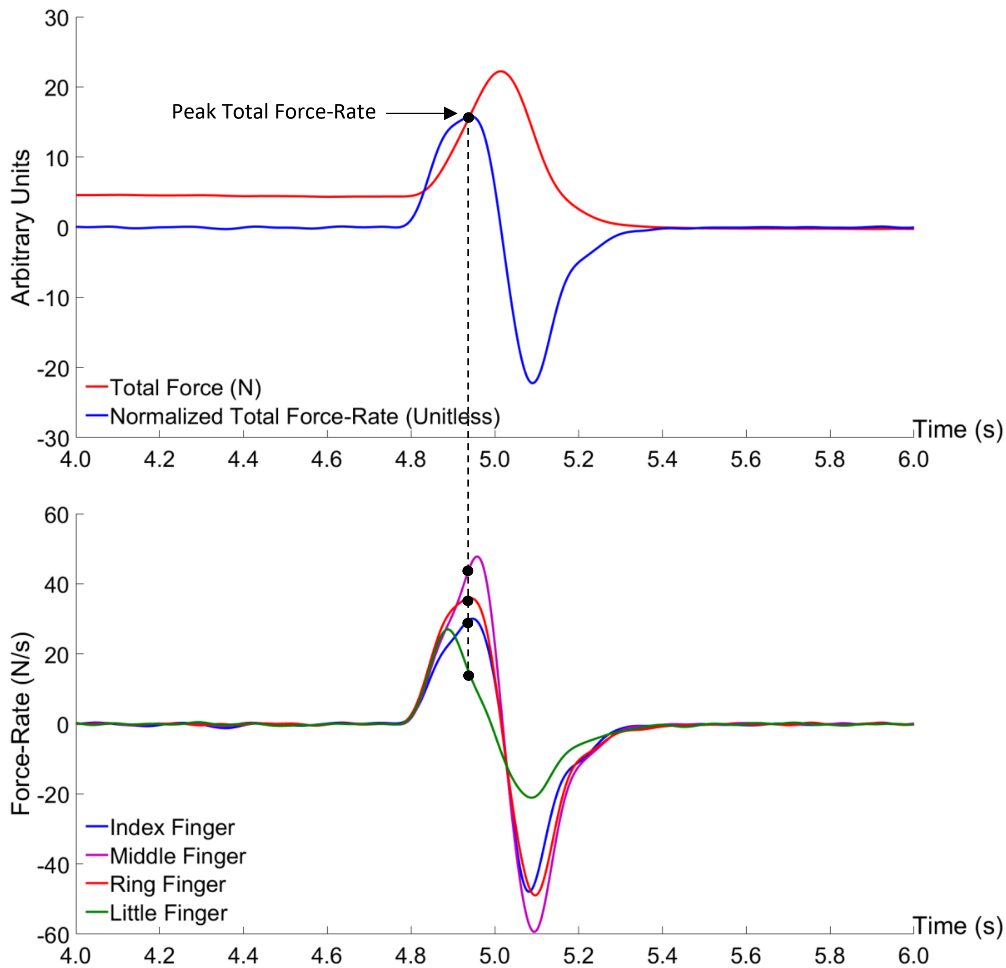


Fig. 2.2: Data from a representative IMRL trial. Participant produced a rapid increase in force and then relaxed to a rested state (up-pulse trial). At the instant of total peak force-rate, the force-rate for each finger was identified.

$$E_{i,j} = 100 \times \frac{\dot{F}_{i,j}}{\dot{F}_{i,i}} \tag{2.5}$$

$$I_j = 100 - (\frac{1}{3}\sum_{i=1}^{3}|E_{i,j}|) \tag{2.6}$$

$$D_j = 100 \times \frac{\dot{F}_j - \dot{F}_{j,\ IMRL}}{\dot{F}_j} \tag{2.7}$$

$$S_j = 100 \times \frac{\dot{F}_{j,\ IMRL}}{\sum_{j=1}^{4}\dot{F}_{j,\ IMRL}} \tag{2.8}$$

where:

i = enslaved finger (I, M, R, L)

j = master finger(s)

$\dot{F} = \frac{dF}{dt}$, for up pulses and

$\dot{F} = -\frac{dF}{dt}$, for down pulses.

2.7 Statistics

All data is presented as the mean ± the standard error. For the pulse trials, four separate four-way mixed Anovas were performed with age (young and older) as a between-subjects factor and with the direction of pulse (up and down), initial force (10%, 25%, 40% MVC) and finger (I, M, R, L) as repeated-measures factors for the following dependent variables: force-rate enslaving, force-rate individuation index, force-rate sharing, and force-rate deficit. A separate four-way mixed Anova was performed on maximum force rate with the same between- and repeated-measures factors. However, the factor finger had five (I, M, R, L, IMRL) instead of four levels.

For the MVC data, four separate two-way mixed Anovas were performed with age (young and older) as a between-subjects factor and finger (I, M, R, L) as a repeated-measures factor for the following dependent variables: MVC, force enslaving, force individuation index, force sharing, and force deficit. A separate two-way mixed Anova was performed with age (young and older) as a between-subjects factor and finger (I, M, R, L, IMRL) as a repeated-measures factor for MVC as the dependent variable. For all statistical models, pairwise comparisons were conducted with Tukey's corrections. All statistics were performed with SAS statistical software (α<0.05). Only significant results will be reported.

3. RESULTS

3.1 Maximum Voluntary Contractions

During maximum force production, both young and older adults produced similar MVCs with the index, middle, ring, and little finger. However, older adults produced a larger MVC with all four fingers (IMRL) than young adults. This was reflected by a significant interaction between age and finger [$F(4,31)=2.96$, $p=0.0353$] (Fig. 3.1A).

The ring finger was the most enslaved. The index, middle, and little finger had similar force enslaving. This was reflected in a significant main effect of finger on enslaving [$F(3,27)=9.97$, $p=0.0001$] (Fig. 3.1B).

The index and little finger were more individuated than the other two fingers. This was reflected in a significant main effect of finger on the individuation index [$F(3,27)=10.00$, $p=0.0001$] (Fig. 3.1C).

During maximum force production with all four fingers (IMRL), the index and middle finger produced the largest force (greatest force sharing), followed by the ring, and then the little finger. This was reflected in a significant main effect of finger on force sharing [$F(3,27)=74.03$, $p<0.0001$] (Fig. 3.1D).

During maximum force production, the index and little finger experienced the greatest force deficit, followed by the middle, and ring finger. This was reflected in a significant main effect of finger on force deficit [$F(3,27)=8.63$, $p=0.0004$] (Fig. 3.1E).

3.2 Maximum Force-Rate

During maximum force-rate production, young adults produced smaller maximum force-rates (MFR) than older adults for the down pulses, but the force rates across

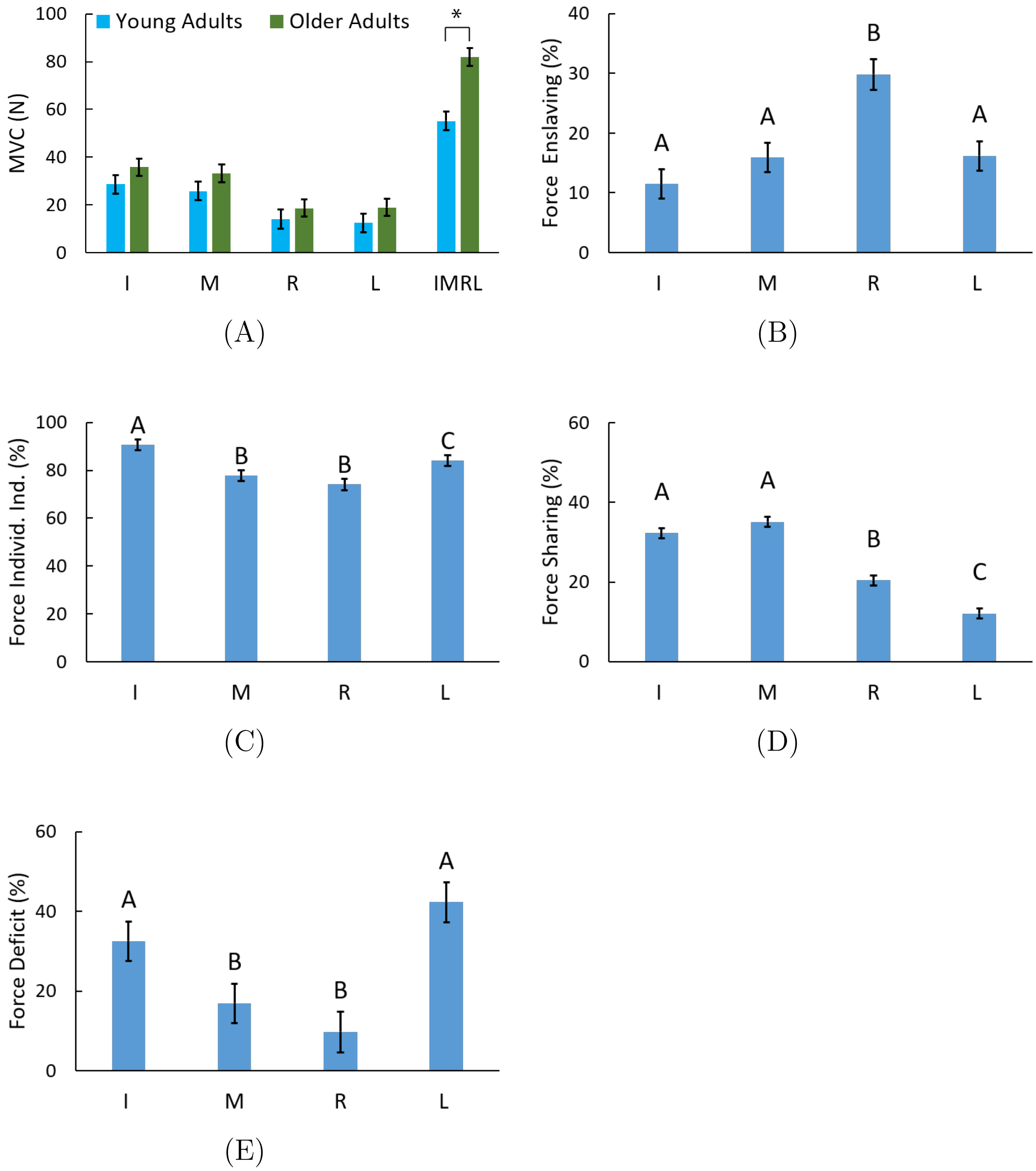


Fig. 3.1: (A) Young and older adult MVC force production of the fingers. (B) Force enslaving of the fingers. (C) The force individuation index of the fingers. (D) Force sharing of the fingers. (E) Force deficit of the fingers.

age were similar for the up pulses. This was reflected in a significant interaction between age and task [$F(1,8)=12.32$, $p=0.008$] (Fig. 3.2A).

The index, middle, ring, and all four fingers (IMRL) produced greater MFRs during up pulses than down pulses. This was reflected by a significant interaction between task and finger [$F(4,36)=20.40$, $p<0.001$] (Fig. 3.2B).

There was a tendency for increased MFR with initial force. In particular, the index and middle finger produced greater MFRs in the 40% initial force compared to the 10% initial force level, and MFR increased with initial force for the IMRL condition. This was reflected in a significant interaction between initial force and finger [$F(8,72)=2.55$, $p=0.0165$].

During down pulses, all four fingers (IMRL) together produced greater MFRs with an increase in initial force level. During down pulses, the index and middle finger produced greater MFRs in the 40% initial force level compared to the 10% initial force level. The middle and ring finger produced similar MFRs across all initial forces during both up and down pulses. This was reflected by a significant three way interaction between task, initial force, and finger [$F(8,71)=2.28$, $p=0.0314$] (Fig. 3.2C).

3.3 Force-Rate Enslaving

The ring finger is more enslaved while producing up pulses than down pulses. The enslaving in the index, middle, and little fingers were similar between up and down pulses. This was reflected by a significant interaction between task and finger [$F(3,27)=3.68$, $p=0.0241$] (Fig. 3.2D). Force-rate enslaving increased with the increase in initial force as reflected by a significant main effect for initial force [$F(2,18)=12.32$, $p=0.004$].

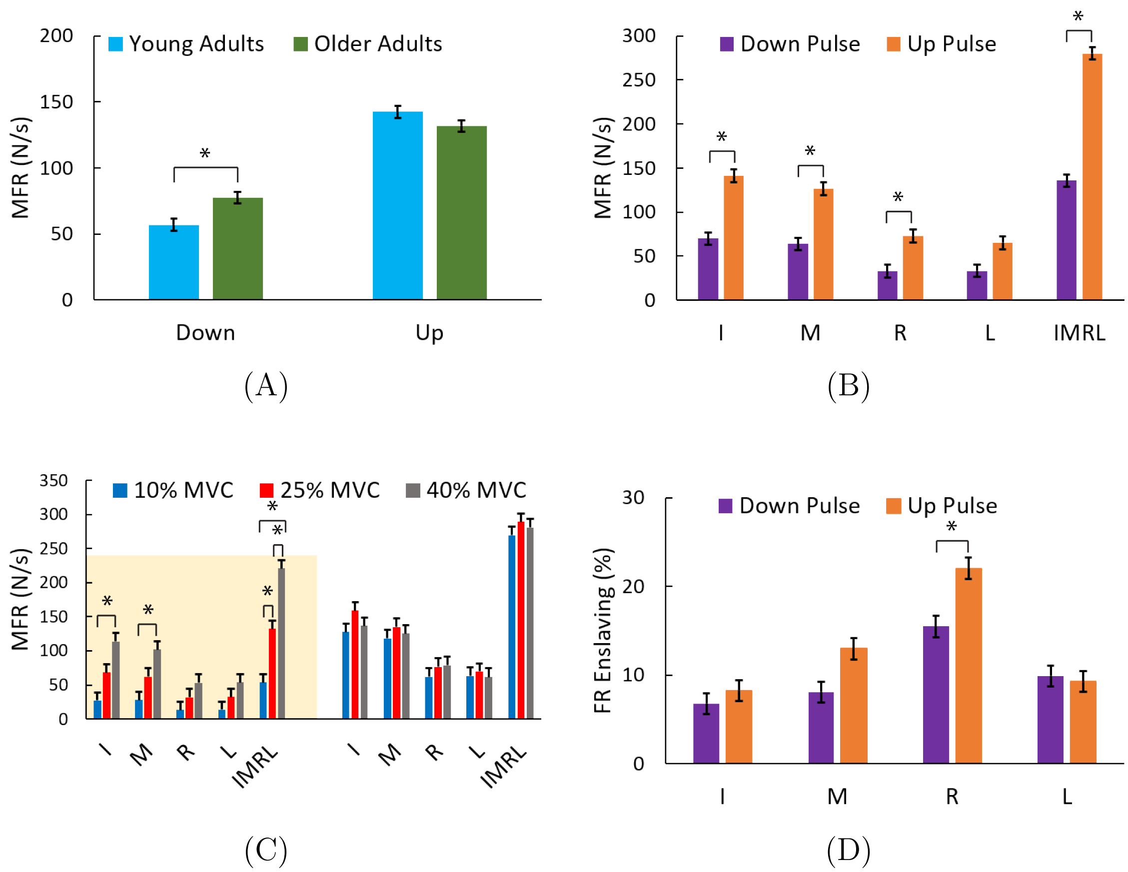


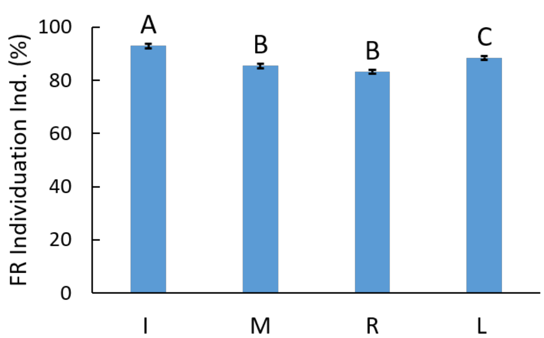
Fig. 3.2: (A) Young and older adult MFR production during up and down pulses. (B) MFR production of the fingers during up and down pulses. (C) MFR production of the fingers across initial force levels during down pulses (shaded area) and up pulses. (D) Force-rate enslaving of the fingers during down and up pulses

3.4 Force-Rate Individuation Index

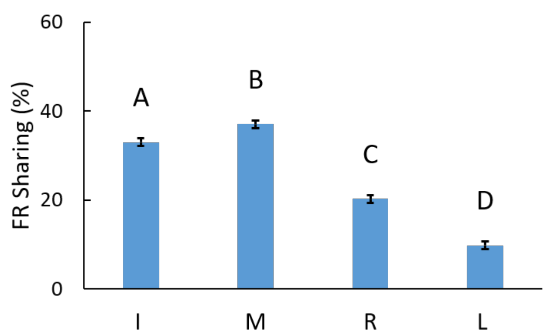
The index finger had the greatest force-rate individuation index followed by the little finger as reflected by the main effect of finger [$F(3,27)=27.50$, $p<0.001$] (Fig. 3.3A). The average force-rate individuation index was greater during down pulses compared to up pulses as reflected by the main effect of task [$F(1,9)=6.87$, $p=0.0278$]. The force-rate individuation index was greater for the 10% initial force level than the 40% initial force level as reflected in the main effect of initial force [$F(2,18)=9.52$, $p=0.0015$].

3.5 Force-Rate Sharing

The middle finger produced the larger force-rate (greatest force-rate sharing) compared to all other fingers. This was reflected by the significant main effect for finger [$F(3,27)=210.50$, $p<0.001$] (Fig. 3.3B).



(A)

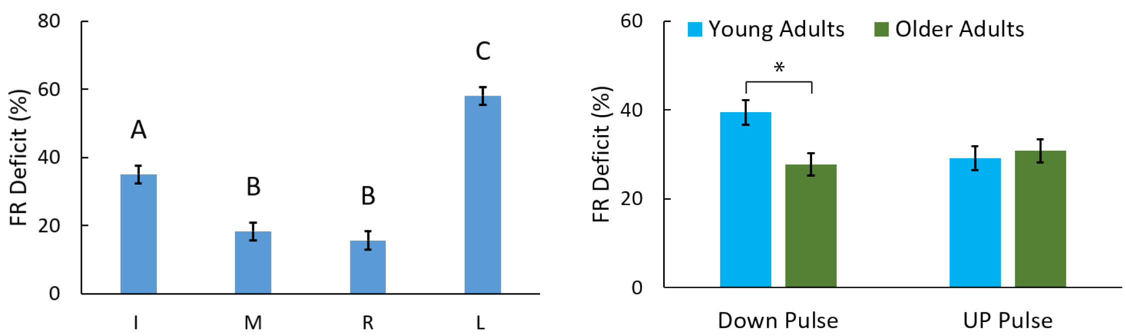


(B)

Fig. 3.3: (A) Force-rate individuation index of the fingers. (B) Force-rate sharing of the fingers.

3.6 Force-Rate Deficit

The little finger experienced the greatest force-rate deficit followed by the index finger as reflected by a main effect of finger [$F(3,27) = 54.17$, $p<0.001$] (Fig. 3.4A). Young adults experienced greater force-rate deficit than older adults during down pulses, but force-rate deficit during the up pulses was similar for both age groups. This was reflected in a significant age by task interaction [$F(1,8) = 6.41$, $p = 0.0352$] (Fig. 3.4B).



(A) (A)

Fig. 3.4: (A) Force-rate deficit of the fingers. (B) Young and older adult force-rate deficit during up and down pulses.

3.7 Visual Comparison of Finger Interactions as Computed with MVC and MFR Measurements

It follows from the statistical results reported above that the interactions between the fingers as quantified by the various metrics (enslaving, individuation, sharing, and deficit) using MVC and MFR values follow similar patterns across the fingers. To illustrate this point, the plots presented above are reorganized and reproduced below (Fig. 3.5A-F). The MVC and MFR values are compared across 3.5A and B, whereas the derived metrics are compared within each of the remaining figures.

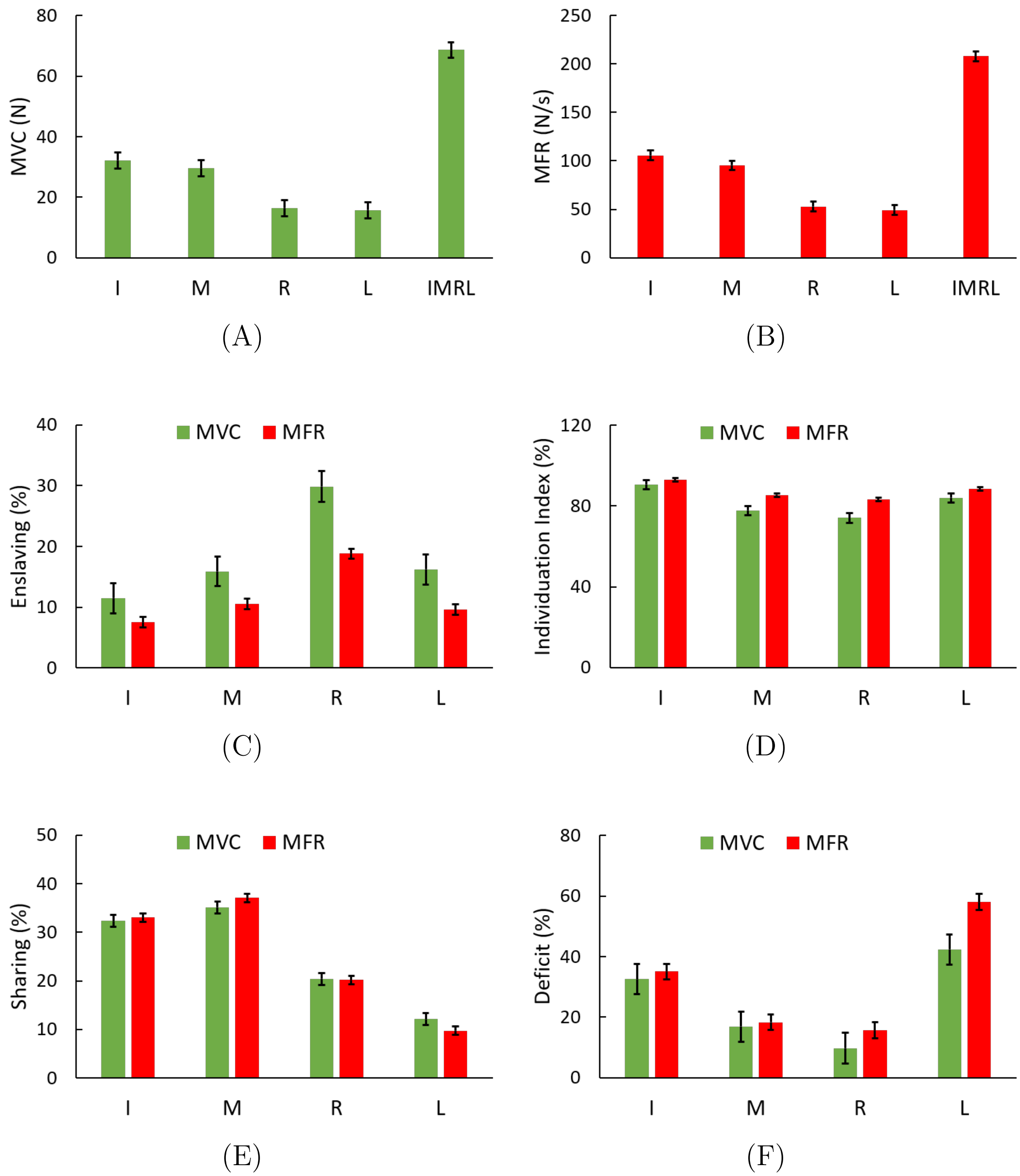


Fig. 3.5: Comparison of finger interdependence patterns computed using MVC and MFR measurements.

4. DISCUSSION

4.1 Maximal Force Production

In our experiment, the largest maximum force was produced by all four fingers concurrently (IMRL), which is consistent with previous studies in isometric finger pressing (Shinohara et al., 2003b; Zatsiorsky et al., 1998). In the single finger conditions, the index and middle finger produced the largest peak forces with no significant difference between the fingers followed by the similar maximal force production of the ring and little finger. In previous studies, the maximal force production among individual fingers varies. The index finger has been reported to produce the largest peak force, followed by the middle, ring, and then the little finger (Shinohara et al., 2003b; Zatsiorsky et al., 1998). The index and middle finger have also been reported to produced the same maximal force (Li et al., 1998). Additionally, the ring and little finger have also been reported to produce similar maximal forces (Shinohara et al., 2003a). Therefore, the maximal force production of the fingers in our experiment are consistent with previous studies.

Older adults typically produce lower peak forces than young adults (Shinohara et al., 2003a; Shinohara et al., 2003b; Oliveira et al., 2008). However, young and older adults have also been found to produce similar maximal forces with individual fingers (Park et al., 2011) and all four fingers concurrently (Olafsdottir et al., 2007a; Olafsdottir et al., 2007b; Tillman and Ambike, 2018). In our experiment, young and older adults produced similar maximal forces with individual fingers. However, older adults produced greater maximal forces while using all four fingers concurrently (81.95 ± 3.7) than young adults (55.19 N ± 3.9). Additionally, the magnitude of the peak force in this condition for the older adults is higher than previously reported (Kapur et al., 2010; Shinohara et al., 2003a; Shinohara et al., 2003b; Tillman and

Ambike, 2018). This is counter-intuitive, because there is significant skeletal muscle loss (sarcopenia) with aging (Carmeli et al., 2002; Carmeli et al., 2003; Dutta, 1997; Baumgartner et al., 1998), and muscle or endpoint forces are dependent on muscle mass. However, strength is also typically associated with weight. There is a positive correlation between strength and BMI for children and adolescents (Lad et al., 2013; Hasan et al., 2016) as well as for older adults (Samson, 2002; Forrest et al., 2018). In our experiment, older adults were significantly heavier than the young adults (OA=89.2 $\pm$ 11.1 kg, YA=67.1 $\pm$ 11.9 kg; $t(16.5)=4.18$; $p<0.001$). Furthermore, the gender ratio was not consistent across the age groups. There were more male participants in the older adult group (7 males) compared to the young adult group (5 males). Both young and older women have lower finger forces compared to the men of similar ages (Shinohara et al., 2003a). These factors may explain the higher strength observed in our older adult group.

4.2 Maximal Force-Rate Production

Averaged across young and older adults, the type of force change, and the initial forces, the greatest maximal force rate (MFR) was produced when all four fingers concurrently performed a quick change in force. In the single finger conditions, the index and middle fingers produced the greatest MFR, followed by the similar MFR production by the ring and little fingers. This pattern of MFR among the fingers is consistent with the pattern of maximal force production among the fingers (Fig. 3.5A and Fig. 3.5B). This observation supports the hypothesis presented in the Introduction that the overall pattern for producing force changes will resemble those for producing maximal forces.

Note that maximal force rate generation may be related to the maximal force production ability. For example, maximal grip force correlates positively with explosive grip force generation in young adults (Watanabe et al., 2011; Ikemoto et al., 2007). Additionally, in athletics, maximal strength has been associated with explosive measures such as peak power and peak rate of force development (Stone et al., 2002). However, such a relation has not been established for finger force production, and this is a promising direction for future work.

Both young and older adults produced similar MFRs during up pulses (Fig. 3.2A). The ability to generate rapid forces during isometric contractions is dependent on the number of motor units activated (motor neuron recruitment speed) and motor neurons discharge action potentials (maximal unit discharge rates) (Maffiuletti et al., 2016). There are physiological changes with age that may influence motor neuron recruitment and discharge rates in older adults such as reduced motor unit firing rates, reduced number of motor units, and reduced size and number of type II muscle fibers (Tieland et al., 2018; Reid and Fielding, 2012; Klass et al., 2008; Barry et al., 2005).

In a study that examined the recruitment and discharge rates of motor units with intramuscular electromyograms, young and older adults performed rapid isometric ankle dorsiflexion to a target (25 %, 50%, and 75% of MVC). Motor unit activity as quantified by the EMG of the tibialis anterior was the same for both young and older adults at the beginning of the contraction but at peak torque-rate older adults had less motor unit activity due to reduced successive motor unit discharge frequencies. Additionally, older adults produced lower peak torque rates than young adults (Klass et al., 2008). Young adults also produced greater peak force-rates than older adults during rapid isometric ankle plantar flexion (Thompson et al., 2014). However, we did not see a difference in peak force-rates with age during rapid force generation in isometric finger pressing. Most studies that measure the ability to generate rapid isometric contractions have been assessed with the muscles of the lower body. It may be possible that physiological changes that affect rapid force generation develop slower in the extrinsic muscles of the hand due to the constant use of the hands during ballistic movements in daily living.

Averaged across initial force and finger, young adults produced lower MFRs than older adults during down pulses (Fig. 3.2A). Voluntary muscle relaxation is attributed to the active inhibition of agonist muscles, perhaps via withdrawal of tonic input to the motor cortex, in addition to the termination of the excitatory drive to the agonist (Rothwell et al., 1998; Motawar et al., 2016; Motawar et al., 2012). There is evidence that in older adults, short interval intracortical inhibition (SICI) is reduced during grip relaxation, and it is accompanied by slower grip force relaxation compared to young adults adults (Opie and Semmler, 2014; Motawar et al., 2016). Therefore, our results are inconsistent with previous findings. This may be explained by the inconsistent experimental paradigms employed for the two age groups: young adults had to activate these inhibitory neural circuits more often than older adults due to the larger number of finger conditions. Therefore, it is possible that activation of these circuits was reduced in young adults over time, which resulted in lower maximal force rates during the down pulses in the young adults.

For both the young and older adults, the average MFR was significantly lower for down pulse than up pulse (Fig. 3.2B). This may be partially because the requirement that the fingers cannot lift off the sensors during force reduction imposed an accuracy constraint on this task. A similar constraint is not present for up pulse tasks. There is some evidence suggesting that although reducing force can be achieved faster than increasing force, it is harder to rapidly achieve a lower force target compared to a higher force target (Ohtaka and Fujiwara, 2016). Therefore, the maximal rates during force decrease in the present work may be limited by the classical speed-accuracy trade-off.

However, it is also known that there are physiological differences in force generation and force reduction. In *slow* isometric contraction studies with young adults, firing rates of motor units at the same force level is slower during force relaxation than force generation (de Luca et al., 1982; Denier van der Gon et al., 1985). Additionally, brain activity is different during finger force increase and force decrease. In *slow*, isometric accurate grip force production using the tripod grasp (fingertip pads of thumb, index, and middle are in contact with object), functional magnetic resonance imaging revealed that the motor cortex was more activated during force generation while the right dorsolateral prefrontal cortex had greater activity during force relaxation (Spraker et al., 2009). It is likely that these factors also influence the force rates observed in this study.

The MFR averaged across age increased with initial force, but this pattern was dominated by the down pulse task and did not appear during the up pulse task (Fig. 3.2C). This difference can also be attributed to the accuracy constraint implicit in the down-pulse tasks. Furthermore, during down pulses, the accuracy task constraint implies that the potential amplitude of force change is smaller for smaller initial forces, which then results in smaller peak force-rates in the master fingers. Therefore, the four-finger tasks experienced a stronger effect of the initial force compared to individual finger tasks, since initial forces were greater in absolute units for that condition.

Maximal force rates during the up pulses did not change with initial force levels (Fig. 3.2C). This is contrary to the expectations laid out in the introduction based on the activation dynamics and mechanical properties of the musculo-tendinous unit (MTU). The fingers are actuated by a redundant set of intrinsic and extrinsic hand muscles, and perhaps, the coordination between these muscles avoids the rate-limit evident in single MTUs. There are no studies on maximal force generation from an initial force in finger pressing tasks. However, rapid force production from initial forces has been studied in athletics, and similar results are reported. In a study, experienced collegiate weight lifters performed isometric mid-thigh clean pulls (rapidly pulling a fixed bar in a standing position) from 4 initial force levels (30, 60, 90, and 120% of 1 Rep Max power clean - equivalent to MVC) while standing on a force plate. Similar to our experiment, the participants were instructed to perform the action as fast and as hard as possible. The peak rate of force development of the mid-thigh clean pulls was similar across all initial force levels. However, this remains a topic for future research.

4.3 Interactions Between Fingers

In maximal force production, the interactions between fingers is assessed with measures such as force enslaving, force individuation index, force sharing, and force deficit. The same measures were computed with the maximal force-rate measurements in this study. The comparison of these measures between peak forces and peak force-rates within our experiment will help assess the difference between strength and explosive measures in finger force production.

In general, enslaving has been attributed to peripheral mechanical coupling, existence of motor units that overlap multiple digits, and overlapping representations of the fingers in the cerebral cortex (Zatsiorsky et al., 2000; Kilbreath and Gandevia, 1994). The average force-rate enslaving was significantly greater during up pulses than down pulses. Perhaps enslaving depends on the magnitude of the force rate (recall that MFR is greater during force increase than during force decrease). This notion is supported by the observation that when force enslaving is measured during sub-maximal force generation, the amount of enslaving may depend on the magnitude of force produced by the master finger (Slobounov et al., 2002). This, however, is speculation, and the physiological differences between force increase and decrease highlighted earlier may also be responsible for this observation.

The ring finger was the most enslaved while the other three fingers had similar enslaving during up pulses. This observation is consistent with maximal force production studies (Fig. 3.5C). There, the ring finger is also the most enslaved finger, followed by the middle finger and then the similar enslaving between the index and little finger (Shinohara et al., 2003a) (Fig. 3.2D). The ring and middle finger are more enslaved due to their anatomical location and stiff connection to the trapezoid and capitate bones (Slobounov et al., 2002). Force-rate enslaving for the index, middle, and little fingers was similar for up and down pulses. However, the ring finger was more enslaved during a up pulse, which may also be attributed to anatomical characteristics previously mentioned.

The magnitude of the force-rate enslaving for each finger is similar to a isometric finger pressing study where young adults produced MVCs with all 15 finger conditions with the dominant and non-dominant hand (Wilhelm et al., 2013). However, typical force enslaving values for each finger in maximal force production studies are larger and resemble the force enslaving in our findings (Shinohara et al., 2003a; Zatsiorsky et al., 1998). This is the first time force-rate enslaving in a maximal force change task has been reported, so it is unknown if the magnitude of the enslaving is large or low. Enslaving has been shown to change based on the type of task. For example, when participants maintain a force level (25%, 50% and 75% of MVC) for 2s, the enslaving (averaged over the maintenance period) for each finger increased proportionally with the force level (Slobounov et al., 2002). In general, force-rate enslaving may be inherently lower than force enslaving due to the type of task and the behavior of the master finger. During MVC production, the master finger continuously produces a downward force, which may cause the enslaved fingers to also produce a downward force. However, during a rapid force change, the master finger first produces a sub-maximal force and then performs a quick transition to either increase or decrease the force. Due to the possibility of lifting the fingers off the sensors, the enslaved fingers are unable to produce similar force changes proportional to the force changes of the master finger. Perhaps, the enslaved fingers compensate for the large force change produced by the master finger by producing small force changes relative to the master finger. In our experiment the enslaved fingers occasionally produced a small force change opposite to the master finger.

Force-rate and force enslaving enslaving was similar between age groups. In maximal force production studies, it has been established that fingers are less enslaved in older adults (Shinohara et al., 2003a). Averaged across fingers, the magnitude of the force enslaving in our experiment (YA=12.5 $\pm$ 0.6 % and OA=10.7 $\pm$ 0.6 %). So, the overall enslaving trends in the right direction, but did not reach statistical significance. The force enslaving in the older adult group is similar to typically reported values ($\sim$ 13%) (Shinohara et al., 2003a; Shinohara et al., 2003b). It is unclear why the enslaving measured for young adults is lower than expected. Force-rate enslaving was also similar between young and older adults. However, it is unclear how the underlying mechanisms of enslaving (peripheral connections and neurological implications) affect finger interdependence during rapid force changes.

The force-rate individuation index reflects the amount of maximal force change a master finger produces if the enslaved fingers did not produce any change in force. Index and little finger had the highest individuation index in both maximal force-rate and force production (Fig. 3.5D). The individuation index may be highest for these two fingers because they are not influenced as much by the tendinous connections of intrinsic muscles compared to the middle and ring finger. The average force-rate individuation index increased in rapid force production. Additionally, the average force-rate individuation index increased from the 10% initial force to the 40% initial force level. The increase in the force-rate individuation index with the type of force change and initial force may be a consequence of the increased maximum force-rate production of the finger within those factors.

The middle finger generated the largest proportion of force change in the total force change of the IMRL condition (force-rate sharing) followed by the index, ring, and little finger. For force sharing, both the middle and ring contributed the most ($\sim$ 30%), followed by the ring and little finger, which is consistent with previous literature (Li et al., 1998; Shinohara et al., 2003a; Shinohara et al., 2003b; Oliveira et al., 2008). Both force-rate and force sharing showed similar sharing across individual fingers (Fig. 3.5E). The novel finding is that fingers follow the same sharing pattern across maximal force and maximal force-rates. Consistent with maximal force production studies, there is no difference in the sharing pattern with age. The same sharing pattern has also been shown in children during isometric finger tip pressing tasks (Shim et al., 2007; Oliveira et al., 2008), in the adapted power grip (only the palm and finger tips are in contact with apparatus) (Vigouroux et al., 2011) and in the manipulation of various bottles during transport (Cepriá-Bernal et al., 2017). Due to the consistency of the sharing pattern across the lifespan and in manipulation of daily object such as plastic water bottles, the sharing pattern of the fingers may be a result of learning to grasp objects in a particular manner from birth.

The little finger experienced the largest force-rate deficit and both the middle and ring finger experienced the least amount of force-rate deficit for both age groups. Additionally, both the index and little finger experienced the greatest force deficit, followed by the middle and then ring finger for both age groups. We found that the little finger experienced the largest amount of deficit and the ring finger experienced the least amount of deficit, which is consistent with maximal force production studies (Shinohara et al., 2003a; Shinohara et al., 2003b; Oliveira et al., 2008) (Fig. 3.5F). With aging, force deficit has been found to increase (Shinohara et al., 2003a; Shinohara et al., 2003b) and sometimes remained the same (Oliveira et al., 2008). A larger force deficit in older adults during isometric finger pressing tasks has been attributed to the lower maximal discharge rates of motor units in the hand muscles (Shinohara et al., 2003a). In our experiment, force deficit was similar across both age groups.

In our experiment, young adults experienced a greater force-rate deficit (averaged across initial force and finger) than older adults during down pulses but not during up pulses (Fig. 3.4B).As mentioned earlier the ability to generate rapid forces during isometric contractions is dependent on maximal unit discharge rates. During up pulses, there was no difference in maximal force-rates between young and older adults (3.2A), which suggests that maximal unit discharge rates were similar across age. Older adults produced greater maximal force-rates than young adults during down pulses (3.2A). However, it is unclear if greater maximal force-rates relates to lower force-rate deficit in older adults since there are physiological difference between rapid force generation and relaxation.

Overall, the comparison of finger interactions between the maximum force and maximum force-rate measures indicates similarity in the observed patterns (Fig. 3.5A-F). However, with the force-rate measurements, maximal rates during force increase and decrease become possible. Such measurements may provide additional clinically relevant information.

4.4 Fatigue

In isometric fatigue finger pressing tasks, maximal force production has been shown to drop after the fatiguing exercise with a 43% decrease in the four finger condition (Danion et al., 2001). To test for fatigue in the older adults, the MVC task was repeated at the end of the experiment. A two-way mixed anova was performed with the repeated measures factors time (pre-experiment and post-experiment) and finger (I, M, R, L, IMRL) for the dependent variable MVC. There was no significant difference between the MVC task at the beginning or the end of the experiment. Due to this result and the rest given to the older adults between trials, the possibility of fatigue in the older adults is unlikely. Although we did not check for fatigue in the young adults, the young adults were given a minimum of one day between experimental sessions. Additionally, both the young and older adults did not report feeling tired during our experiment.

4.5 Limitations

The main limitation of this experiment is the different experimental design between the young and older adults (see Table 2.1). The young adults performed more tasks with more finger combinations than the older adults. Furthermore, for the young adults, the experiment was divided into two sessions that were conducted on different days. In contrast, the older adults performed the experiment in a single session. Due to these difference in experimental design, the comparisons across age should be viewed with caution.

4.6 Future work

There are several lines of research for the future. First, the functional and clinical implications of MFR need to be established. For example, do MFRs correlate with clinical measures of manual dexterity, such as time taken to complete pegboard tasks?

Second, although it is known that strength training improves manual dexterity, one needs to establish if these functional gains can be improved with training that focuses on increasing MFR. Finally, the relation between maximal finger force and MFR needs to be established. Such a relation would imply that measurement of one of the two characteristics of finger behavior will suffice for some clinical purposes.

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APPENDIX

APPENDIX

A.1 Rest in Experimental Sessions

Table 1: Approximate duration of each task and rest given for each young adult participant.

Task	Duration of Task	Amount of Rest
Session 1:		
MVC Task	3 mins (30 trials x 6s)	10 mins (30 breaks x 20s)
Break		8 mins
Down Pulse 10%	5 mins (30 trials x 10s)	10 mins (30 breaks x 20s)
Break		8 mins
Down Pulse 40%	5 mins (30 trials x 10s)	10 mins (30 breaks x 20s)
Session 2:		
Down Pulse 25%	5 mins (30 trials x 10s)	10 mins (30 breaks x 20s)
Break		8 mins
Up Pulse 40%	5 mins (30 trials x 10s)	10 mins (30 breaks x 20s)
Break		8 mins
Up Pulse 10%	5 mins (30 trials x 10s)	10 mins (30 breaks x 20s)
Break		8 mins
Up Pulse 25%	5 mins (30 trials x 10s)	10 mins (30 breaks x 20s)
Estimated Time	33 mins (task)	85 mins (rest)

Table 2: Approximate duration of each task and rest given for each older adult participant.

Task	Duration of Task	Amount of Rest
MVC Task	1 min (10 trials x 6s)	5 mins (10 breaks x 30s)
Break		8 mins
Up Pulse 25%	2 mins (10 trials x 10s)	5 mins (10 breaks x 30s)
Break		8 mins
Up Pulse 10%	2 mins(10 trials x 10s)	5 mins (10 breaks x 30s)
Break		8 mins
Up Pulse 40%	2 mins (10 trials x 10s)	5 mins (10 breaks x 30s)
Break		8 mins
Down Pulse 10%	2 mins (10 trials x 10s)	5 mins (10 breaks x 30s)
Break		8 mins
Down Pulse 40%	2 mins(10 trials x 10s)	5 mins (10 breaks x 30s)
Break		8 mins
Down Pulse 25%	2 mins (10 trials x 10s)	5 mins (10 breaks x 30s)
Break		2 mins
MVC Retest	1 min (10 trials x 6s)	5 mins (10 breaks x 30s)
Estimated Time	14 mins (task)	90 mins (rest)

A.2 Normalized Impulse Analysis

Rapid force increase and decrease of the fingers were also measured with an impulse (integral of a force over a time interval). The methodology for computing the impulse is outlined below.

For each down and up pulse trial within a given master finger condition, this time interval was identified from the total force time curve. The start and end of the pulse were defined as the instants when the force rate dropped below 2% of the peak force rate for the first time while stepping backward and forward in time from the instant of the peak force rate, respectively. Therefore, for each down and up pulse trial, the impulse of each finger was calculated by taking the integral of the force time curve of each finger from the same time coordinates as the start and end of the pulse of the total force time curve. The magnitude of an impulse depends on the time between the start and the end of the pulse. Participants will generate quick changes in force at different times. Therefore, impulse was normalized by the duration of the pulse.

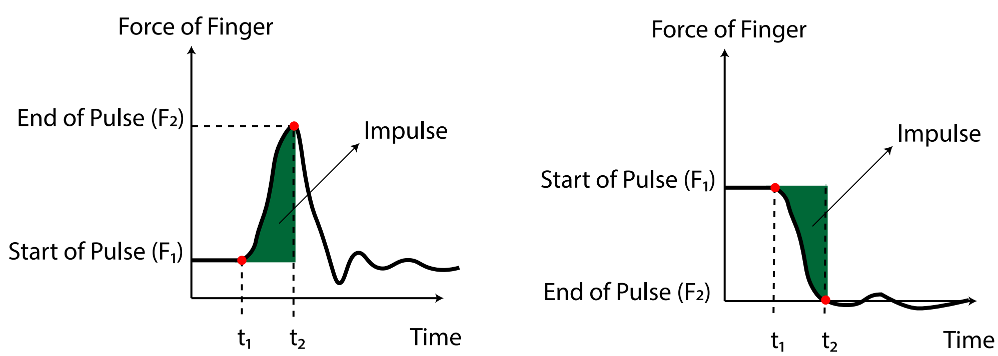

Fig. 1: A representative figure of the impulse calculation (green shaded area) for an individual finger in the up pulse (left) and down pulse (right) trial. The red markers show the start and end of the pulse for each trial.

For both the down and up pulse task, young adult participants had four normalized impulse values (N) for 15 different master finger conditions and older adult participants had four normalized impulse values (N) for 5 different master finger conditions. These normalized impulse values were used to compute maximum normalized impulse, normalized impulse enslaving, normalized impulse individuation index, normalized impulse deficit, and normalized impulse sharing for the down and up pulses. The same structure of the mathematical equations from the MVC and force-rate analysis was also used. Therefore, normalized impulse, normalized impulse enslaving, normalized impulse deficit, and normalized impulse sharing for both down and up pulse were computed the same way but with normalized impulses as the inputs (see Equations 1 2, 3, 4, & 5, respectively.). Normalized impulse enslaving and individuation index was averaged across each enslaved finger.

$$I = \frac{1}{t_2 - t_1}\left[\int_{t_1}^{t_2} F(t)\ dt - [(t_2 - t_1) \times F_1]\right] \tag{1}$$

$$E_{i,j} = 100 \times \frac{I_{i,j}}{I_{i,i}} \tag{2}$$

$$II_{i,j} = 100 - |100 \times \frac{I_{i,j}}{I_{i,i}}| \tag{3}$$

$$D_j = 100 \times \frac{I_j - I_{j,\ IMRL}}{I_j} \tag{4}$$

$$S_j = 100 \times \frac{I_{j,\ IMRL}}{\sum_{j=1}^{4} I_{j,\ IMRL}} \tag{5}$$

where:

i = enslaved finger (I, M, R, L)

j = master finger(s)

F_1 = start of pulse

The maximal force change abilities and measures of finger interdependence (enslaving, individuation, sharing and deficit) obtained using impulse measures resembled closely those obtained from maximal force rates. Therefore, these results are not reproduced here. However, it is useful to know that these two measures of rapid finger force production in isometric conditions are compatible, and therefore, redundant.

A.3 Force-Rate Enslaving Matrix

Table 3: Young adult force-rate production averaged across finger for rapid force increases.

YA: Rapid Force Increase					
Variable	IF	Index	Middle	Ring	Little
MFR	10%	144.7 ± 24.6	124.9 ± 25.1	61.1 ± 9.0	62.6 ± 10.8
	25%	163.1 ± 20.2	147.9 ± 20.7	81.0 ± 13.4	74.8 ± 9.4
	40%	139.4 ± 15.1	134.9 ± 20.7	77.4 ± 12.4	60.3 ± 9.2
Enslaving	10%	8.8 ± 3.3	12.9 ± 2.7	17.2 ± 2.2	7.6 ± 0.9
	25%	9.2 ± 2.2	12.8 ± 1.6	22.6 ± 3.7	10.1 ± 2.6
	40%	11.6 ± 2.2	11.9 ± 1.6	20.6 ± 2.3	12.4 ± 2.4
Individuation	10%	92.5 ± 1.0	89.2 ± 1.3	81.5 ± 4.5	89.7 ± 1.1
	25%	91.2 ± 2.2	86.6 ± 2.0	81.5 ± 3.1	85.6 ± 2.7
	40%	94.4 ± 0.7	82.6 ± 2.1	77.8 ± 2.7	86.8 ± 1.8
Deficit	10%	37.2 ± 5.1	4.7 ± 13.1	-4.2 ± 13.7	52.2 ± 9.8
	25%	37.0 ± 5.9	16.5 ± 9.9	10.9 ± 8.2	70.7 ± 4.8
	40%	26.8 ± 7.3	23.2 ± 9.6	16.9 ± 9.5	56.9 ± 7.8
Sharing	10%	31.8 ± 3.0	37.7 ± 2.7	20.7 ± 2.4	9.8 ± 2.3
	25%	33.6 ± 3.2	38.3 ± 4.5	20.2 ± 1.9	8.0 ± 2.5
	40%	37.2 ± 5.1	34.1 ± 3.6	19.8 ± 1.8	8.5 ± 1.5

Table 4: Young adult force-rate production averaged across finger for rapid force decreases.

YA: Rapid Force Decrease					
Variable	IF	Index	Middle	Ring	Little
MFR	10%	24.2 ± 2.1	24.6 ± 2.1	11.3 ± 1.2	11.5 ± 1.5
	25%	61.4 ± 5.2	55.2 ± 3.9	27.6 ± 2.9	26.9 ± 3.0
	40%	102.9 ± 9.6	92.2 ± 6.3	46.5 ± 5.5	42.0 ± 5.8
Enslaving	10%	3.4 ± 2.2	4.0 ± 1.9	13.9 ± 3.2	7.9 ± 2.3
	25%	11.5 ± 4.1	10.7 ± 3.0	19.7 ± 3.0	11.2 ± 2.5
	40%	10.8 ± 2.5	12.2 ± 2.1	23.4 ± 3.7	13.2 ± 2.8
Individuation	10%	94.1 ± 1.4	87.8 ± 2.9	89.4 ± 2.1	92.3 ± 1.2
	25%	91.6 ± 1.8	84.7 ± 3.8	80.5 ± 3.8	89.5 ± 2.2
	40%	92.3 ± 1.3	80.9 ± 4.1	80.1 ± 2.8	86.7 ± 1.7
Deficit	10%	45.0 ± 9.5	42.9 ± 4.5	13.2 ± 10.8	55.5 ± 12.5
	25%	39.5 ± 9.1	31.6 ± 7.1	28.6 ± 8.0	65.8 ± 8.3
	40%	36.0 ± 10.2	33.0 ± 5.8	27.3 ± 7.3	55.0 ± 6.9
Sharing	10%	31.2 ± 4.1	33.5 ± 1.5	24.1 ± 3.3	11.2 ± 2.6
	25%	36.0 ± 5.5	37.3 ± 4.1	18.3 ± 1.8	8.4 ± 2.1
	40%	35.8 ± 5.3	35.6 ± 4.5	18.3 ± 1.7	10.3 ± 1.7

Table 5: Young adult force-rate production averaged across finger for rapid force increases.

OA: Rapid Force Increase					
Variable	IF	Index	Middle	Ring	Little
MFR	10%	111.4 ± 12.0	111.8 ± 13.0	63.2 ± 10.2	64.6 ± 8.0
	25%	155.1 ± 23.1	122.8 ± 19.2	72.4 ± 10.0	65.0 ± 11.3
	40%	133.8 ± 16.8	116.8 ± 14.5	80.4 ± 8.5	63.5 ± 7.1
Enslaving	10%	5.3 ± 0.7	9.7 ± 2.6	21.4 ± 6.2	6.7 ± 1.7
	25%	5.1 ± 0.9	11.6 ± 2.3	22.7 ± 5.3	8.8 ± 2.5
	40%	9.4 ± 1.8	18.9 ± 3.6	27.7 ± 5.2	10.0 ± 2.2
Individuation	10%	93.6 ± 1.3	88.6 ± 1.6	87.2 ± 3.6	85.8 ± 5.6
	25%	89.8 ± 2.4	83.0 ± 4.0	86.1 ± 2.7	88.5 ± 2.5
	40%	89.5 ± 2.4	79.9 ± 5.2	79.1 ± 4.2	83.3 ± 2.1
Deficit	10%	25.2 ± 11.9	20.7 ± 7.8	4.9 ± 10.6	56.4 ± 7.0
	25%	42.2 ± 7.5	5.9 ± 7.6	18.1 ± 11.5	59.6 ± 9.9
	40%	31.5 ± 10.2	13.2 ± 10.9	25.9 ± 8.4	65.7 ± 5.8
Sharing	10%	32.6 ± 3.7	34.3 ± 2.1	21.7 ± 1.5	11.4 ± 1.9
	25%	31.7 ± 3.6	39.9 ± 2.7	19.9 ± 1.8	8.5 ± 1.3
	40%	33.4 ± 5.1	35.8 ± 3.3	22.0 ± 2.4	8.7 ± 1.1

Table 6: Older adult force-rate production averaged across finger for rapid force decreases.

OA: Rapid Force Decrease					
Variable	IF	Index	Middle	Ring	Little
MFR	10%	30.5 ± 3.4	31.2 ± 3.0	15.8 ± 1.9	16.0 ± 2.2
	25%	75.6 ± 6.1	69.3 ± 8.2	35.9 ± 4.2	37.7 ± 7.3
	40%	124.9 ± 8.7	112.1 ± 12.9	60.1 ± 7.0	65.7 ± 10.4
Enslaving	10%	3.3 ± 2.1	3.6 ± 2.2	7.5 ± 2.4	9.8 ± 4.1
	25%	4.6 ± 2.1	7.1 ± 1.9	11.9 ± 3.8	9.6 ± 2.2
	40%	7.2 ± 2.7	10.9 ± 2.1	16.6 ± 3.7	7.8 ± 1.1
Individuation	10%	94.5 ± 1.3	89.7 ± 1.9	85.9 ± 4.1	92.8 ± 1.0
	25%	96.1 ± 0.7	86.5 ± 3.0	84.5 ± 3.2	91.0 ± 1.5
	40%	94.8 ± 0.8	85.1 ± 3.1	84.3 ± 2.2	88.8 ± 2.7
Deficit	10%	29.6 ± 10.4	23.0 ± 5.7	15.9 ± 10.9	46.2 ± 13.6
	25%	39.0 ± 7.1	-0.3 ± 7.9	8.8 ± 10.6	51.4 ± 9.8
	40%	31.3 ± 10.5	5.5 ± 7.0	21.30 ± 6.9	60.9 ± 5.2
Sharing	10%	31.6 ± 4.1	37.4 ± 3.0	19.4 ± 2.1	11.6 ± 1.6
	25%	28.1 ± 2.2	41.7 ± 2.2	19.9 ± 1.8	10.3 ± 2.0
	40%	32.7 ± 4.1	39.1 ± 2.5	18.3 ± 1.9	9.9 ± 2.0