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Aging-Related Changes in Hand Intrinsic and Extrinsic Muscles and Hand Dexterity : an MRI Investigation

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ABSTRACT

Object : The purpose of this study was to investigate aging-related changes of intrinsic and extrinsic hand muscles in their strength, cross-sectional area and volume, force control, and multi-digit synergies. It was hypothesized that aging would negatively affect distal muscles (intrinsic muscles) more than proximal muscles (extrinsic muscles).

Method : Nine young and eleven older right-handed participants underwent MRI scans of the hand and forearm. Muscle cross-sectional areas and volumes of the intrinsic and extrinsic hand muscles were determined.

Result : Muscle volume of the intrinsic muscles were larger in the younger group than the older group while muscle volume of the extrinsic muscles did not differ. For the cross-sectional area, both the intrinsic and extrinsic muscles of the younger group were larger than the older group. The maximum strength of the intrinsic muscles of the young group was 31% greater than the older group (399.1±26.4 vs 270.2±22.9 Ncm, $p < 0.05$) while the extrinsic muscles showed no significant difference. Although the elderly group showed a trend of decreased force control and multi-digit synergies, no statistical differences were found. These findings indicate aging-related decreases in hand muscle size and strength affect intrinsic muscles more than extrinsic muscles, thus supporting the hypothesis that sarcopenia affects the muscle size and strength of distal muscles more than proximal muscles.

Conclusion : The aging-related decreases in hand muscle size and function were more apparent in intrinsic hand muscles, located more distally, than extrinsic muscles, located more proximally.

Keywords : Aging, Intrinsic Hand Muscle, Extrinsic Hand Muscle, MRI

Ⅰ. Introduction

Interactions with the external environment require a proficiently functioning hand that can perform complex actions, such as pressing, pinching, gripping, and manipulation. Decreases in hand strength and dexterity in older adults can impair the hand steadiness (Laidlaw, Kornatz, Keen, Suzuki, & Enoka, 1999), multi-finger synergy (Shim, Hsu, Karol, & Hurley, 2008; Shim, Lay, Zatsiorsky,& Latash, 2004), and performance of activities of daily living (Carmeli, Patish, & Coleman, 2003; Kallman, Plato, & Tobin, 1990; Rantanen et al., 1998). A loss of muscle fibers and changes in muscle fiber length due to aging can also accompany the losses in hand and finger strength and dexterity (Carmeli et al., 2003).

Hand-finger movements are precisely controlled by over 20 muscles that can be categorized by location into two groups: intrinsic (i.e., within the hand) and extrinsic (i.e., within the forearm) muscles. Early investigations showed that the intrinsic hand muscles were responsible for fine motor control or dexterity, whereas the extrinsic hand muscles controlled gross motor performance and major force production by the hand (Long, Conrad, Hall, & Furler, 1970). Previous studies have

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demonstrated varied activation of intrinsic and extrinsic muscles while pressing with different parts of the fingers, by examining the different tendinous insertions and force generating abilities (Li, Zatsiorsky, & Latash, 2000; Shinohara, Latash, & Zatsiorsky, 2003). The extrinsic hand muscles are the main force generators at the distal phalanges while the intrinsic hand muscles are the main force generators at the proximal phalanges. This results from the intrinsic hand muscles having insertions into the proximal phalanx of individual fingers and the extrinsic hand muscles having insertions into the distal phalanx of multiple fingers.

Several investigators have suggested that distal muscles might experience greater aging-related loss of strength than proximal muscles (Christ et al., 1992; Rice, Cunningham, Paterson, & Lefcoe, 1989; Viitasalo, Era, Leskinen, & Heikkinen, 1985). Specifically, one study showed that more distal intrinsic muscles are affected more by aging than more proximal extrinsic muscles (Viitasalo et al., 1985). This claim was made by comparing the reduction in hand grip strength (42% decrease) to elbow flexion strength (35% decrease). In support of this finding, Shinohara and colleagues found that forces produced by the intrinsic finger flexors showed a greater aging-related decline than the extrinsic finger flexors (Shinohara, Latash, et al., 2003). Although both studies reported that the strength of distal muscles were affected more by aging than proximal muscles, neither examined whether a similar pattern exists in muscle size. Examination of the muscle size can be done by measuring the muscle cross-sectional area (CSA) or volume.

A direct relationship between muscle size and strength has often been reported in previous studies (Anakwe, Huntley, & McEachan, 2007; Holzbaur, Murray, Gold, & Delp, 2007; Kallman et al., 1990). Forearm circumference is correlated with grip strength, such that a forearm circumference difference greater than 2 cm between contralateral arms can predict diminished grip strength (Anakwe et al., 2007). Using advanced imaging techniques, Holzbaur and colleagues showed a significant positive relationship between upper limb muscle volume and isometric force production (Holzbaur et al.,2007). Both muscle size and strength have been shown to decline in the process of aging (Kallman et al., 1990), albeit at slightly different rates (Lynch et al., 1999). However, there is a knowledge gap in the relationship between the muscle size and strength of the intrinsic and extrinsic hand muscles and how they are affected by aging.

The purpose of this study was to examine the aging-related differences in muscle size and function of the intrinsic and extrinsic hand muscles. Based on the findings of previous investigations, we hypothesized that older adults would show 1) a greater decrease in the volume and CSA of the intrinsic hand muscles (i.e., distal muscles) than extrinsic muscles (i.e., proximal muscles), 2) a greater decrease in hand muscle strength of the intrinsic as compared to extrinsic muscles, and 3) a overall reduction in hand dexterity compared to the younger group.

II. Methods

1. Ethical approval

The procedures of this study were approved by the University of Maryland (USA) Institutional Review Board. Prior to participating in this study, all subjects gave informed written consent to the procedures approved by the University of Maryland's Institutional Review Board.

2. Subjects

Nine young (mean ± SE: 23.9 ± 1.6yr old) and eleven older (mean ± SE: 71.4 ± 1.6yr old) females participated in this study (Table 1). All subjects were screened for thefollowing: a) right-handedness according to the Edinburgh Handedness Inventory (Oldfield, 1971), b) low to moderate

Table 1. Subject Characteristics (n=20)

	Young (n = 9)	Elderly (n = 11)	*p* value
Age(yrs)	23.9 ± 1.6	71.4 ± 1.6	.000
Hand Length(cm)	17.6 ± 0.3	17.5 ± 0.3	.689
Hand Width(cm)	7.5 ± 0.1	7.4 ± 0.1	.125
Forearm Length(cm)	25.2 ± 0.4	23.9 ± 0.4	.089
Height(cm)	164.0 ± 1.9	160.0 ± 3.3	.330
Body mass(kg)	59.2 ± 2.5	62.9 ± 4.1	.481
BMI(kgm^2)	22.0 ± 0.7	25.1 ± 1.9	.178

Values are mean ± SE. p-values are from analysis of variance (ANOVA) results risk health status according to the American College of Sports Medicine Risk Stratification Guidelines (Association, 1998; Medicine, 2006), c) no professional typing or playing musical instrument experience, and d) no history of upper extremity disorders (including surgery, arthritis, neurological issues, or neurological disorder). The subjects were recruited to have similar hand length, hand width, forearm length, height, and weight to minimize inter-group anthropometric differences.

3. Magnetic resonance imaging (MRI) procedure and data analysis

A 1.5 T scanner (Signa HDe, General Electric Healthcare) was used to acquire T1-weighted images. Each subject underwent two scans, one scan of the right forearm (TR/TE, 5.8/1.9; matrix, 1024 × 1024 ; FOV, 40 × 40cm; number of acquisitions, ~150; slice thickness, 2mm; contiguous slices with no gaps; transverse plane) and one scan of the right hand (TR/TE, 6/1.9; matrix, 1024 ×1024; FOV, 25 × 25cm; number of acquisitions, ~175; slice thickness, 1mm; contiguous slices; transverse plane). Only the right upper limb was imaged. The MRI sequences and parameters were established to minimize inter-slice noise, and slice interpolation within and between scans, and to maximize image matrix size, contrast-to-noise ratio, spatial resolution, and subject tolerance. The scanning parameters were similar to a previous study (Eng, Abrams, Smallwood, Lieber, & Ward, 2007) but slightly modified for this study. The total acquisition time for each subject, including setup, was approximately 30 minutes.

The MRI images were imported into Analyze 8.1 (Analyze Direct, Lenexa, KS) where a binary mask was created and the images were corrected prior to further analysis. Different tissues were separated by different threshold intensities (Fig. 1). Muscle volume (MV) was determined by an interpolation algorithm that uses the area of the identified muscle voxels in each image and the number of slices. The extrinsic hand muscles were determined from the forearm region of interest (ROI). The forearm ROI was defined as the region between the most proximal slice that includes the proximal portion of the ulna and the most distal slice that includes the distal radius, inclusive. The intrinsic hand muscles were determined from the hand ROI. The hand ROI was defined as the region between the most distal slice that includes the distal radius, exclusive, and the slice that incorporates the most distal portion of the finger.

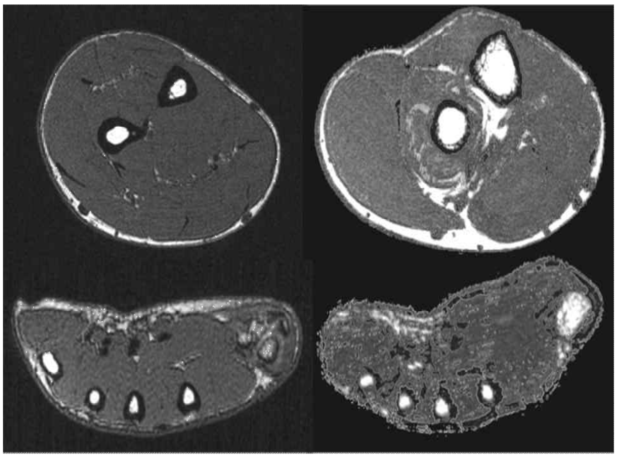


Figure 1. MR images showing the cross sectional slices of the forearm(top) and the hand(bottom). The images on the left are raw files prior to segmentation to differentiate various tissues. The images on the right show different tissues defined by different colors. The tissue of interest, muscle, is shown with the red border.

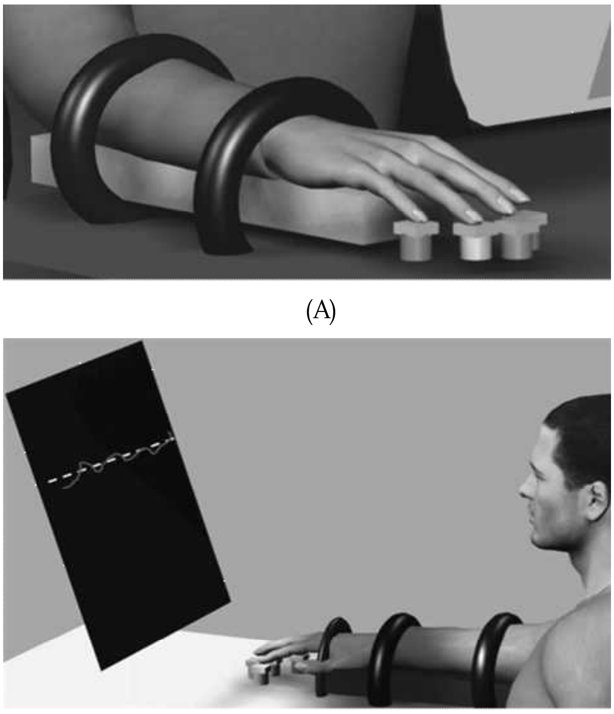
The CSA of the intrinsic (IM) and extrinsic muscles (EM) were also determined from the MR images. Procedures for separating different tissues were the same as those described for MV. The CSA of IM was taken from the median slice between the carpal metacarpal joint and the metacarpal phalangeal joint. The slice with the maximal muscle area was not taken for the CSA because it contained many muscles that contribute to thumb movement. Since this study examined finger forces produced predominately by the intrinsic hand muscles of the 2nd to 5th digits, the slice selected was to mainly contain the lumbricals and interossei, and be easily identifiable for all subjects. The CSA of EM was defined as the largest muscle area in a single forearm slice (Klein, Allman, Marsh, & Rice, 2002).

To assess the validity of the MRI analysis, water phantoms were imaged and the volumes were determined by the analysis technique described above. Eight volumes (25, 50, 75, 125, 200, 325, 525, and 825 mL) were used. The smallest volume was chosen to represent the approximate size of the smallest intrinsic hand muscle and the largest volume was selected to represent a value slightly greater than the total forearm volume in an adult female. Each intermediate volume used was the sum of the previous two volumes used. This method is similar to the permutation of the golden ratio. There was a high linear correlation between the known volumes and calculated volumes (r2 = 0.9997). The known volume was the volume measured by a volumetric flask and the calculated volume was the volume determined from the MRI analysis. Every subject's IM and EM were each analyzed three times by a single examiner. The coefficient of variation for the single examiner was 2.113% for the intrinsic and 1.137% for the extrinsic hand muscles.

Two approaches were considered for selecting the image for determining extrinsic muscle CSA – either taking the slice at a fixed anatomical location or taking the slice with the greatest muscle area. On average, the largest extrinsic muscle area for the subjects in this study was located at about 20% of the distance from the proximal ulna to the distal radius. The EM CSA determined from this fixed anatomical location revealed similar results to the slice representing the greatest muscle area. In order to allow the results of this study to be comparable to a previous study (Kleinet al., 2002), this study reported the extrinsic muscle CSA as the slice representing the greatest muscle area in the forearm data set. For the intrinsic muscle CSA, only the fixed slice was taken, as explained earlier.

4. Maximum voluntary force (MVF) and constant force production tests

For the MVF and constant force production tests, a customized device that included four of one-dimensional force sensors (gray cylinders in Fig. 2A) and four amplifiers (Models 208 M182 and 484B, Piezotronics, Inc) for four fingers (2nd-5th digits) was used. Sensors were fixed on a wooden table. Delran blocks were affixed to the sensors' top surface to prevent subjects from directly touching the sensors and to minimize signal changes due to heat from the fingers. Signals from the sensors were conditioned, amplified, and digitized at 100 Hz using a 16-bit A/D board (PCI 6034E, National Instruments Corp.). A custom software program made in LabVIEW (LabVIEW 7.1, National Instruments Corp.) was used for testing and recording. The force produced by a single-finger force or the total of all-four finger forces applied on the sensors was displayed on the monitor as online visual feedback to the subjects (Fig. 2B).


(A)

(B)

Figure 2. Panel A shows the experimental settings for the right hand: one-directional (compression) sensors (gray rectangles) were fixed to the table. Delran blocks (yellow objects) are fixed to the tops surface of the sensors. The subject places either the distal phalange or proximal phalange of each finger on the block. The sensor positions are adjustable for different hand sizes. Velcro straps are used to secure the forearm, wrist and hand (black objects). Panel B shows subject watching the computer screen to perform a task while sitting in a chair. The dotted line (white) represents a force template. The solid line(red) represents the actual force produced.

For the MVF and constant force production tests, all subjects sat facing the computer monitor with the right forearm flat and secured on a wooden panel. Subjects were asked to rest either the distal phalange (DP) or the proximal phalangeal (PP) joint of each finger on the Delran piece attached to the sensor. In order to remove the gravitational effects of the fingers and any passive finger flexion or extension due to the position of the fingers, the force signals for the initial 0.5 seconds were averaged for each finger and subtracted from the signals after the initial 0.5 seconds. Thus, only the force actively produced by the subject was shown on the monitor.

Subjects performed five conditions for the isometric MVF test: four single-finger conditions and one four-finger condition using the right hand. Two trials were administered for each condition and the second trial was used for data analysis. The same procedure was repeated at the DP and PP. The DP elicit near maximal force production by the extrinsic hand muscles and minimal force by the intrinsic muscles (Harding, Brandt, & Hillberry, 1993; Li et al., 2000). Thus, extrinsic hand muscles are considered the focal force generators at the distal phalanx. In contrast, forces produced at the PP are produced primarily by the intrinsic hand muscles. For the DP condition, the sensor was anteriorly translated such that the middle of the DP rested on the middle of the block. For the PP condition, the sensor was posteriorly translated such that the proximal interphalangeal joint also rested on the middle of the block. During each trial, all fingers remained on the blocks, and subjects were asked to produce maximum isometric flexion force with the specified task finger(s) over a 3 second interval.

For the constant force production test, a yellow horizontal dotted line which represented 20% of the four-finger MVF value (Oliveira, Hsu, Park, Clark, & Shim, 2008; Shim et al., 2008) for the particular subject was shown on the computer screen as the force profile for subjects to follow (Fig.2B). The actual force produced was superimposed as a solid red line over the profile to provide real-time visual feedback of the force being produced. Each trial was 15 seconds and subjects were asked to produce four-finger pressing forces to match the force profile template during the last 12 seconds. Each subject performed twelve trials with at least one-minute intervals between trials and two-minute intervals between tasks. Trials with noticeable finger or wrist joint movements were rejected and repeated by the subjects.

The force data from the MVF and constant force production test were digitally low-pass filtered with a 2nd-order, zero-lag Butterworth filter at 25 Hz cutoff frequency (Shim, Olafsdottir, Zatsiorsky, & Latash, 2005; Winter, 1990). For each MVF trial, the instantaneous maximum force produced by task finger(s) was measured. The data were used to detect or calculate the maximum voluntary torque (MVT) and normalized strength (MVTnorm). For each constant force production trial, the force produced between the 5th and 12th second was used for the follow-up analysis. MVT was determined by multiplying the forces, recorded from the individual fingers at both the DP and PP with the moment arm. The moment arm was defined as the distance between the metacarpophalangeal (MCP) joint and middle of the distal phalanx for the DP condition, and between the MCP joint and proximal interphalangeal joint, for the PP condition. Additionally, normalized strength(MVTnorm) was calculated by taking the ratio of MVT and muscle CSA (Kim et al., 2010; Shim et al., 2004).

Delta Variance (DV) was calculated as an index of multi-digit synergy under the framework of the uncontrolled manifold analysis (Latash, Scholz, Danion, & Schoner, 2001; Schoner, 1995). When DV >0, negative co-variations among the individual fingers dominate, suggesting multi-finger synergy which improves performance on this motor task. When DV <0, positive co-variations among the individual fingers dominate, suggesting multi-finger synergy which hinders performance on this motor task. Detailed calculations can be found in previous studies (Latash et al., 2001; Shim et al., 2008; Shinohara, Scholz, Zatsiorsky, & Latash, 2004).

Root mean squared error (RMSE) was calculated as the average deviation from the force template over 12 trials. The inverse of RMSE was calculated to quantify force control accuracy (FC).

$$RMSE = \left[\sum_{n=1}^{12} \sqrt{\sum_{t=5}^{12} \left|F(t) - F_{target}\right|^2 / t}\right] / n \, / MVF \qquad (1)$$

$$FC = 1/RMSE \qquad (2)$$

Where F(t) is the time trajectory of four-finger force, Ftarget is the target force (20% of the four-finger MVF), t is the time in seconds with which the analysis was performed (t = 7), n is the total number of trials (n = 12), and MVF is the maximal voluntary force produced by four fingers together.

5. Overall hand dexterity

The Jebsen Taylor Hand Function (JTHF) test (Jebsen, Taylor, Trieschmann, Trotter, & Howard, 1969) and Lafayette Grooved Pegboard (PB) were used to assess overall hand dexterity. The time to completion was recorded for the JTHF and PB test. The JTHF test is composed of 7 individual tests. The time for individual tasks for the JTHF test was summed and examined as one measure (Hummel et al., 2005). Performance on the JTHF and PB test was quantified by taking the inverse of the total time taken to complete each task.

6. Statistics

Standard descriptive statistics and ANOVA with the between-subject factor of AGE (two levels: older and young) and within-subject factor MUSCLE (two levels: intrinsic and extrinsic) were performed on MV, CSA, MVT, MVTnorm, DV, and FC. One-way ANOVA with the factor of AGE was performed on JTHF and PB. The level of significance was set at $p < 0.05$. Bonferroni corrections were made on significant results. Values were presented as mean ± standard error (SE).

III. RESULTS

1. Muscle Size : volume and CSA

Muscle volumes were larger in the young subjects compared to the older subjects for the extrinsic muscle group, while muscle volumes were not significantly different for the intrinsic muscle group (Figure 3A). The results were supported by ANOVA with main effects of AGE [$F_{(1,18)} = 15.6$, $p < 0.01$] and MUSCLE [$F_{(1,18)} = 920.1$, $p < 0.01$] and a AGE x MUSCLE interaction [$F_{(1,18)} = 4.4$, $p < 0.05$]. The extrinsic hand muscles were also significantly larger than intrinsic hand muscles for both young and older subjects ($p < 0.01$).

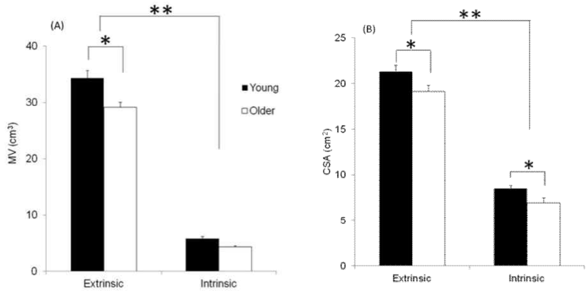


Figure 3. Panel A shows volume, in absolute units, of extrinsic and intrinsic muscles for young and older subjects. MV-muscle volume. Panel B shows the cross sectional area (CSA), in absolute units, of extrinsic and intrinsic muscle for young and older subjects. *indicates significant ($p < 0.05$) difference between age group; **indicates significant($p < 0.01$) difference between muscle group.

Muscle CSA was greater in young subjects for both the intrinsic (18%) and extrinsic (10%) muscle groups as compared to the older subjects (Figures 3B). The extrinsic muscle CSA was significantly greater than the intrinsic muscle CSA. These results were supported by a two-way ANOVA with main effects of AGE [$F_{(1,18)} = 9.8$, $p < 0.01$] and MUSCLE [$F_{(1,18)} = 400.5$, $p < 0.01$]. The interaction effect of AGE x MUSCLE was not significant [$F_{(1,18)} = 0.3$, $p = 0.61$].

2. Strength

Maximum voluntary torque (MVT) produced by the intrinsic muscles of the young subjects was 31.2% greater than the older subjects ($p < 0.05$) (Figure 4A). However, maximal torque produced by the extrinsic muscles of the young subjects was not significantly greater than the older group ($p = 0.36$). The MVT values differed significantly across the intrinsic and extrinsic muscles for both young and older groups ($p < 0.05$). The results were supported by a two-way ANOVA with a significant AGE x MUSCLE interaction [$F_{(1,18)} = 43.1$, $p < 0.001$].

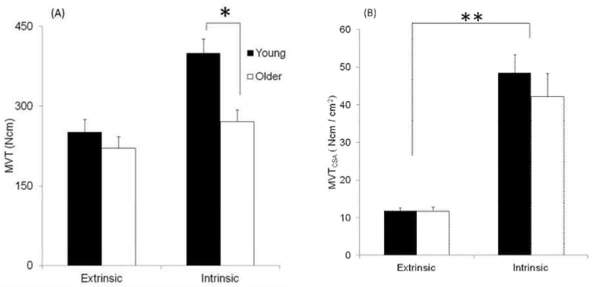


Figure 4. Panel A shows extrinsic and intrinsic muscle strength for young and older subjects. MVT- maximal voluntary torque. Panel B shows extrinsic and intrinsic muscle strength normalized by the cross sectional area for young and older subjects. MVT_{norm}- normalized maximal voluntary torque (C). *indicates significant ($p<0.05$) difference between age group; **indicates a significant ($p<0.01$) difference between muscle group.

Normalized strength (MVT_{norm}) was calculated as the ratio between MVT and muscle CSA. The MVT_{norm} of the extrinsic muscles was approximately equal between young and older subjects. The MVT_{norm} of the intrinsic muscles was 13.4% greater in the younger subjects as compared to older subjects, but did not reach statistical significance (Figure 4B). However, in both the young and older groups, the intrinsic muscles showed a greater normalized strength than the extrinsic muscles. The results were supported by a two-way repeated-measures ANOVA with a significant effect of MUSCLE [$F_{(1,18)} = 81.3$, $p < 0.001$]. Calculation of MVT_{norm} using CSA and muscle volume yielded similar results (not shown in figures).

3. Force control accuracy

There was no significant factor or interaction effect found in force control accuracy. Despite the statistically non-significant effect (p =0.066), younger subjects appeared to have a trend of greater force accuracy (Figure 5A).

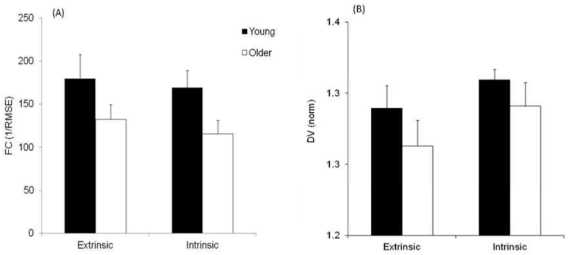


Figure 5. Panel A shows force control accuracy (FC) of the extrinsic and intrinsic muscle for young and older subjects. FC represented as the inverse of root means square error (RMSE). Panel B shows extrinsic and intrinsic muscle delta variance (DV), for young and older subjects. DV is a measure of multi-finger synergy. DV was normalized by each subject's four-finger maximal voluntary force.

4. Delta Variance

No significant statistical effect was found in DV (Figure 5B), although young subjects appeared to have a trend of having greater DV values as compared to older subjects.

5. Hand dexterity

Overall hand dexterity tests showed that young subjects performed about 32.5% and 29.1% better than older adults in the JTHF test and PB test, respectively (Figure 6A and 6B). This result was supported by one-way ANOVA with significant effects of AGE in the JTHF test [F(1,18) = 20.4, $p < 0.001$] and PB test [F(1,18) = 31.4, $p < 0.001$].

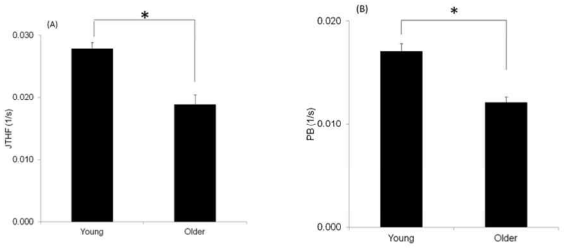


Figure 6. Panel A shows performance on the Jebsen Taylor Hand Function (JTHF) test for young and older adults. Panel B shows performance on the Grooved Pegboard (PB) for young and elderly adults. S-seconds; *indicates a significant ($p < 0.001$) difference between age groups.

IV. DISCUSSION

This study showed that aging-related atrophy and strength decline was evident in muscles controlling the hands and fingers. Sarcopenia was more pronounced in intrinsic muscles (i.e., distal hand muscles) than extrinsic muscles (i.e., proximal hand muscles). The decline in both size and strength was expected since muscle size and strength are known to have a direct relationship (Anakwe et al., 2007; Holzbaur et al., 2007; Kallmanet al., 1990; Lynch et al., 1999).

Both CSA and MV were used to examine muscle size. The CSA and MV results were similar, though each conveys unique information. CSA is composed of muscle fibers aligned in parallel, while muscle volume also includes fibers aligned in series which determine muscle length. It has been reported that muscle contraction force is proportional to CSA, whereas shortening velocity is proportional to fiber length (Lieber, 1986). Declines in CSA are likely a contributing factor to the aging-related decreases in strength (Jubrias, Odderson, Esselman, & Conley, 1997; Macaluso et al., 2002). Maximum voluntary torque or MVT produced by the older subjects was less than young subjects at both the distal proximal phalangeal sites. This result is consistent with many previous findings for pressing (Oliveira et al., 2008; Shinohara, Latash, et al., 2003), pinching (Imrhan & Loo, 1989), or prehension (Shim et al., 2004). The aging-related decrease in joint torque by extrinsic muscles was 11.8% versus 32.3% by intrinsic muscles. A previous study also found a greater difference in pressing strength by the intrinsic muscles as compared to the extrinsic muscles (Shinohara, Latash, et al., 2003). This study supports the notion that distal muscles are more affected by age than proximal muscles (Christ et al., 1992; Shinohara, Latash, et al., 2003; Viitasalo et al., 1985). However, a report by Doherty suggests that strength in the proximal and distal muscles of the upper and lower extremities experience a similar rate of sarcopenia (Doherty, 2003).

Normalized strength (also referred to as muscle quality) has been used as a more appropriate indicator of muscle function than strength or muscle mass alone (Roubenoff & Hughes, 2000). In this study, MVT_{norm} was quantified as a measure of normalized strength of both the intrinsic and extrinsic muscles. The results showed that normalized strength did not differed significantly between young and older subjects in both muscle groups, although MVT_{norm} of intrinsic muscles was, on average, 13.4% less in older subjects. This may suggest that aging reduces strength and muscle size in a similar manner. The lack of a difference may be due to subject sex and the muscle group since a previous study found that the decline in normalized strength was more profound in men versus women and lower extremity versus the upper extremity (Lynch et al., 1999). Other studies have also reported that large[r] muscles often lose strength due to both aging and reduced physical activity (Evans, 1995; Roubenoff & Hughes, 2000), for example the knee extensors (Frontera, Hughes, Lutz, & Evans, 1991; Macalusoet al., 2002) and the elbow flexors (Klein, Rice, & Marsh, 2001).

Muscle size has been reported to be directly associated with strength production (Anakwe et al., 2007; Holzbaur et al., 2007; Kallmanet al., 1990; Lynch et al., 1999), with the loss of muscle size and muscle fiber mainly responsible for the aging-related decrease in muscle strength (Doherty, 2003). The finding that both intrinsic muscle strength and size undergo a greater aging-related decrease suggests that the greater sarcopenia of the intrinsic muscles may contribute to a greater aging-related decrease in the strength of intrinsic muscles as compared to extrinsic muscles. The authors recognize that maximal force production can be affected by multiple factors and muscle size only addresses one aspect of it.

Other possible reasons for the decline in strength include neural and hormonal factors. There is evidence suggesting that motor units of more distal muscle groups decrease while those of the proximal muscle groups remain relatively constant. The motor units supplied by the median and ulnar nerve have been reported to decrease after 60 years of age, with the thenar and dorsal interossei decreasing significantly (Doherty & Brown, 1997; Galea, 1996; Galganski, Fuglevand, & Enoka, 1993). However, motor units in the biceps brachii remain relatively constant. Motor units of the thenar muscle group have also been reported to become largest yet conduct slower (Doherty & Brown, 1997; Doherty, Vandervoort, Taylor, & Brown, 1993). One study even suggested that the core of sarcopenia lies in the loss of α-motor neuron innervations that accompany aging (Brown, 1972). Additionally, the decline in estrogen output accompanying menopause could in hit the production of catabolic cytokines acting directly on muscles (De, Sanford, & Wood, 1992; Pottratz, Bellido, Mocharla, Crabb, & Manolagas, 1994; Ralston, 1994).

The constant force production task in this study employed multiple fingers and the experimental setup allows the distinction between force generated from the intrinsic and extrinsic hand muscles (Li et al., 2000; Shinohara, Latash, et al., 2003). The absence of a significant aging related difference in force control accuracy and multi-finger synergy index may be attributed to the magnitude of the target force used. Our group previously used 20% of maximum voluntary force as the target force (Oliveira et al., 2008) and our current study also employed the same. Keoghe reported a more pronounced aging-related difference in force control accuracy when the force production task became more challenging (Keogh, 2006). Shinohara et al (Shinohara, Li, Kang, Zatsiorsky, & Latash, 2003) used a more challenging task than ours by employing 40% of the subjects' maximum voluntary force for a motor task.

It seems that multi-finger synergies are affected more by aging in motor tasks where greater force production is required. Delta Variance of force has been used as a measure of multi-finger synergy. The results showed a nearly identical multi-finger synergy level between young and older subjects. The difference was less than 3%. Previous studies, requiring subjects to produce a constant force of greater magnitude, showed significant differences in multi-finger synergy measures between young and older subjects (Shim et al., 2004; Shinohara et al., 2004). A challenging motor task such as dynamically changing force production may elicit the aging-related difference in multi-finger synergy more readily since older subjects show decreased anticipatory synergy adjustments (Olafsdottir, Yoshida, Zatsiorsky, & Latash, 2007) to the changing force and lower adaptive ability to control dynamically changing forces (Sosnoff, Vaillancourt, & Newell, 2004). Similar to the explanation for force control, the ability to perform more challenging motor tasks seems to be more affected by the process of aging.

The scanning parameters were established to mimic previous studies that image extrinsic hand muscles (Eng et al., 2007; Holzbaur et al., 2007) while minimizing the scan time to allow for subject comfort. As a result, the images obtained in this study were not suitable for individual muscle segmentation. In order to obtain an image quality that would allow for individual muscle segmentation, the scan time required would increase from 6-7 minutes per scan to nearly thirty minutes. Older adults already reported slight discomfort with the 6-7 minute scan for various reasons. Sub-millimeter slices with no gaps between slices were used to account for the small extrinsic and intrinsic muscles. Having larger slice thicknesses or adjacent slice gaps might increase random error from the interpolation process. Although a previous study showed that a few representative slides could predict the muscle volume of a lower extremity (Tracy et al., 2003), no study has been conducted to verify this for the upper extremity.

Overall hand dexterity was measured by the grooved PB and JTHF tests. Performance from both tests, as expected, suggested aging-related decreases in overall hand dexterity. The time to complete the grooved PB and individual tasks of the JTHF test was similar to previous reports of young (Schmidt, Oliveira, Rocha, & Abreu-Villaca, 2000; Jebsenet al., 1969) and older subjects (Hackel, Wolfe, Bang, & Canfield, 1992). The performance of hand dexterity was not related to muscle size or strength. Other factors, including those previously mentioned, may affect the performance on these functional tests, including overall usage and neural innervation.

This study has certain limitations to be addressed. For example, the finger pressing protocol measured forces in flexion, but the automated segmentation technique used for the MRI analysis did not separate individual muscles or group muscles by muscle action or function. Rather, the muscles were separated by location as described in a previous (Shinohara, Latash, et al., 2003). Future studies should group muscles according to their function, such as flexion, extension, abduction, and adduction may provide further insights regarding the mechanisms of aging. The authors also recognize that aging-related changes in muscle configuration and composition may cause the intensity of scanned muscle images to differ from the intensity of muscle for younger adults. For example the hydration levels of total body fat-free mass may differ between young and older subjects (Heymsfield et al., 1993). It is possible that this difference may cause discrepancies in determining the muscle size of young and older adults. However, because of the small muscle area of fat free mass of the hand, relative to the total body fat free mass, it is unlikely to account for large hydration shifts between the age differences described in this study. Moreover, others have not observed significant increases in the hydration of fat-free mass (Chumlea, Guo, Zeller, Reo, & Siervogel, 1999; Lesser & Markofsky, 1979).

V. Conclusion

This study found aging-related decreases in hand muscle size and muscle strength, and overall hand dexterity. The aging-related decreases in hand muscle size and function were more apparent in intrinsic hand muscles, located more distally, than extrinsic muscles, located more proximally. This finding provides support for the hypothesis that distal muscles for hand function are more affected by sarcopenia than proximal muscles.

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