Understanding finger mechanics and motor control in young and elderly

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Understanding finger mechanics and motor control in young and elderly

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"Begin at the beginning, and go on till you come to the end: then stop."
—Lewis Carroll, Alice in Wonderland
Chapter 1

1. Introduction

Aging is a universal detrimental process which limits the range of activities and the quality of life. After the age of 60, there is a steady decline in muscle mass and an accompanying decreasing capacity to generate muscle force. Some 28 years ago, this process has been termed sarcopenia (Rosenberg, 1989; Rosenberg, 1997). Over the years, the definition of sarcopenia has expanded and is nowadays used to encompass all the neurological, metabolic, hormonal, nutritional and physical-activity-associated changes in skeletal muscles related to aging (Cruz-Jentoft et al., 2010). Sarcopenia has a significant effect on the control and stability of the muscles of elderly and can thereby cause problems in day-to-day living (Balagopal et al., 1997; Dutta and Hadley, 1995). It is considered a major cause for the loss of mobility, independence and frailty in elderly (Roubenoff, 2001). Although many studies have been performed on the effects of aging on the mobility of elderly, the effects of aging on hand dexterity is often overlooked.

Through touching and grasping, the hand provides an important link between our body and the outside world. Although the human hand has an unbelievable level of manual dexterity, some of the underlying mechanisms are still largely unknown. Finger motion can be severely limited by disorders, but also by the effects of aging (Chammas et al., 1995; Contreras-Vidal et al., 1998; Giampaoli et al., 1999; Rantanen et al., 1999; Stegemoller et al., 2015). Hands undergo many changes with age, such as the decline in skeletal muscle mass and deficiencies in muscle structure, reduced neural control and changes in the peripheral nervous system (Carmeli et al., 2003; Laidlaw et al., 2000; Warabi et al., 1986). Although pieces of the puzzle have been elucidated, a complete picture of the effects of aging on the hand has not yet been recreated. There are many internal (genetics, diseases, etc.) and external (physical activities) factors that influence the control of the aging hand (Carmeli et al., 2003). Age related diseases, such as osteoarthritis, arthritis and especially osteoporosis, are regularly at the forefront in hand muscle degeneration studies, but so far the effects of normal, healthy aging on the hand and its functions are not fully understood.

An important feature of manual dexterity is finger independence. It has been shown that both young and elderly are not fully capable of independent force and movement control of the individual fingers of the hand. Some studies have reported an increased finger force independence with aging during static finger pressing tasks, as indicated by a decrease in force exerted by the non-instructed fingers (Kapur et al., 2010; Li et al., 2000; Oliveira et al., 2008; Shinohara et al., 2003a). Finger independence has so far
mainly been studied for single joints of a finger and single-finger tasks. However, movements of all three finger joints as well as movements of multiple fingers moving simultaneously, better resemble the finger movements in daily life. In this manuscript finger movement independence for young and elderly will be studied for unrestricted, single and multiple finger flexion tasks.

The following sections will first discuss the structures of the hand, from bones to muscles and tendons in healthy, young hands to form a baseline from which we can then discuss the changes that occur to these structures with aging and the effect these adaptations might have on finger independence.

1.1. Hand structure

For all digits the anatomical design is broadly identical, i.e. consisting of proximal, middle and distal phalanges (Fig. 1). As an exception, the thumb has only a proximal and distal phalanx. The fingers thus consist of three joints: the metacarpophalangeal joint (MCP) between the metacarpals and proximal phalanges, the proximal interphalangeal joint (PIP) between the bottom and the middle phalanges and the distal interphalangeal joint (DIP) between the middle and the distal phalanges (Fig. 1). The MCP joints allow motion around two axes, namely flexion/extension and abduction/adduction, while the interphalangeal joints are only capable of motion around one axis, namely flexion/extension.

*Figure 1: Bones of the hand: DP = distal phalangeal, MP = middle phalangeal, PP = proximal phalangeal, M = metacarpal bones, MCP = metacarpophalangeal, PIP = proximal interphalangeal, DIP = distal interphalangeal.*
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There are two groups of muscles that control finger movement: intrinsic and extrinsic muscles. A hand has 11 intrinsic and 15 extrinsic muscles (Carmeli et al., 2003). The extrinsic muscles, originating in the forearm, control gross finger performance (Johnston et al., 2010). The principal actions of the extrinsic muscles are flexion and extension of the fingers and wrist. Several extrinsic muscles are multi-digit, i.e. one muscle belly is connected to multiple fingers, and act as flexors and extensors at the DIP and PIP joints. The extrinsic muscles that flex the fingers include the m. flexor digitorum profundus (FDP) and the m. flexor digitorum superficialis (FDS). This thesis focuses on the FDS muscle. The FDS can easily be measured with surface electromyography (sEMG) as it lies close to the skin, while the FDP muscle lies deeper and is more accurately measured by using needle EMG, which is an intrusive and less comfortable method (Jacobson et al., 1998). Some studies have looked into the individual muscle activations of the FDP muscle and found that it has an incomplete functional subdivision (Reilly and Schieber, 2003). The workings of the FDS muscle are so far largely unknown. As the anatomy of the FDS muscle is more complex than the FDP, it could be that the FDS muscle is more functionally divided. The FDS lies superficial to the FDP in the anterior compartment of the forearm. It has a very complex structure with both a superficial and a deeper layer. The superficial layer forms two muscle bellies that give rise to the ring and middle finger tendon, while the deeper layer divides into two muscle bellies that are connected to the tendons for the index and little finger (Ohtani, 1979). Even though an unique FDS muscle belly exist for every finger, some muscle fibers act in series with multiple distal FDS tendons (Frohse, 1908; Maas et al., 2017; Ohtani, 1979) (Fig. 2). This way, forces can be exerted on more than one finger when certain muscle fibers are activated (Maas et al., 2017). The extensor digitorum (ED) is the extrinsic extensor finger muscle. The ED muscle is located on the back of the forearm and originates from the lateral epicondyle of the humerus after which it divides into 4 tendons. Its primary function is to extend the fingers and the wrist.

The origins and insertions of the intrinsic finger muscles reside within the hand. The intrinsic muscles can be divided into four groups: thenar (for the thumb), hypothenar (for the little finger), interossei, and lumbricals. Both the interossei and the lumbricals balance finger movement (Liss, 2012), control the abduction and adduction of the fingers and are responsible for finger flexion at the MCP joint (Landsmeer and Long, 1965). It has been shown that during large finger movements, such as studied in this manuscript, the intrinsic finger muscles are less active than the extrinsic muscles (Buford et al., 2005).
Figure 2: Drawing of the FDS muscle. (Fig. 60 from Frohse, 1908).

The fibers of the FDS tendons have a spinal arrangement and flatten, fork and fold around the FDP muscle to reach their insertions into the distal phalanx of the hand (Sharma and Maffulli, 2005). The FDS and FDP tendons in the distal palm and fingers form a tendon network, which is a particular feature of the tendons in the hand. In the carpal tunnel, tendon interconnections are present between the FDP tendons (Leijnse et al., 1997). Although no studies so far found tendon interconnections between the FDS tendons, our own dissection data have revealed that some connections can be found between the little and ring finger tendons in some subjects and these may also limit finger independence (Fig. 3). The extensor tendons of the hand splay out from under the extensor retinaculum and head towards the fingers. The tendons are linked to each other by a collection of fibrous bands known as juncturae tendinum. The bands control the spacing of the extensor tendons, channel the forces between them and coordinate the extension of different fingers (von Schroeder and Botte, 2001).
1.2. Finger independence

Although the hand shows a tremendous capacity for dexterity, there are limitations to independent individual finger movement. Many studies have shown that when a person voluntarily moves or produces force with one finger, the other fingers produce involuntary motions (movement enslaving) and forces (force enslaving) (Lang and Schieber, 2004; van Duinen et al., 2009; Zatsiorsky et al., 2000). Finger enslaving has been attributed to both mechanical and neural factors. Mechanical factors consist of epimuscular myofascial force transmission (Maas et al., 2003) and the above mentioned mechanical coupling between the tendons (Leijnse et al., 2008). The neural factors include drive to motor units that innervate muscle fibers located in muscle heads associated with multiple fingers, spatial overlap of motor cortex areas for movements of different fingers and diverging central commands due to projections of single motor cortex neurons to several motor neurons in the spinal cord (Sanei and Keir, 2013; Schieber and Hibbard, 1993; van Duinen and Gandevia, 2011). One study has looked at how much these factors influence finger independence by studying passive and active single finger movements (Lang and Schieber, 2004). They found that mechanical coupling was a major factor of limited finger independence, especially for the index, middle and ring fingers. Only one finger joint (the MCP) was free to move during the instructed tasks studied.

So far, finger independence has been studied mainly during static finger pressing tasks (involuntary force production) or during finger flexion and extension tasks when the range of finger joints was limited. In static and dynamic force production tasks, it has been shown that finger enslaving is the largest for the neighboring finger (Mirakhorlo et al., 2017; Zatsiorsky et al., 2000). Movement enslaving studies have shown that the thumb and index finger have the largest independence, while the ring and middle

Figure 3: Tendon connection (white arrow) between ring finger and little finger tendon. When the tendon of the ring finger was manually pulled, both the ring and little finger were flexed at the MCP joint. Own dissection data example, 2014.
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Finger show most involuntary movement of non-instructed fingers (Kim et al., 2008; Lang and Schieber, 2004; Li et al., 2004). All these results were found for single-joint or single-finger tasks. Taking all finger joints into consideration could influence the degree of finger independence. As both the FDS and the FDP muscles insert on the PIP and MCP joints, movement of multiple finger joints will increase the extent of the muscle-tendon unit length changes of the extrinsic muscles (Li et al., 2000). Thus, constraining part of the finger joints influences finger independence, whereas studying all finger joints when they are free to move better represents natural finger movements.

Most previous studies limited the quantification of the extent of finger independence, such as the enslaving index, to a single outcome parameter based on the total range of motion (ROM). An evaluation of the whole trajectory of finger movement might give further insights into finger independence, especially in a range of independent movement of an instructed finger.

1.3. Effects of aging

1.3.1. Muscle mass

The most common and well-known change in muscles that occurs with aging is the loss of muscle mass. Almost 45% muscle mass loss can be demonstrated between 60 and 80 years of age (Carmeli et al., 2003; Demontis et al., 2013; Short et al., 2005; Tseng et al., 1995). There are changes in both the fiber size and fiber number with aging in most skeletal muscles. Several MRI and ultrasonography studies have shown that the described loss of muscle tissue is accompanied by infiltration of fat and connective tissue (Kent-Braun et al., 2000; Sipila and Suominen, 1994). One study showed that with aging there was 27% and 45% more fat and connective tissue for the arm flexors and extensors (Rice et al., 1989). Elderly have thus less contractile tissue and more noncontractile tissue, which in turn results in an increased stiffness and a decreased force production capability (Carmeli et al., 2003; Kent-Braun et al., 2000; Roig et al., 2010; Stenholm et al., 2008). The effects of aging on both the extrinsic and the intrinsic hand muscles have not often been studied and results are scarce. Some studies have shown that the upper forearm muscles show a decline in the amount of muscle fibers with age (Carmeli et al., 2003; Lateva et al., 1996). One study applied force at the proximal phalanges (intrinsic muscles are focal force generators) and the distal phalanges (extrinsic muscles are focal force generators) and found that intrinsic hand muscles exhibit a greater decrease in force production than extrinsic muscles with aging (Shinohara et al., 2003a).
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1.3.2. Motor unit properties

It has been shown that the number of motor units (MUs) in a muscle rapidly declines at a rate of about 3% per year from the age of 60, which at the age of 80 thus leads to a 60% loss of the amount of MUs (Campbell et al., 1973). This denervation process, is counteracted by a reinnervation process: when an alpha-motor neuron dies, adjacent neurons reinnervate the orphaned muscle fibers through collateral sprouting (Campbell et al., 1973; Deschenes, 2011; Larsson, 1995; Vandervoort et al., 1987). This process leads to an increase in the size of the still existing MUs, which leads to a loss of fine movement control (Piasecki et al., 2016).

Not only does the number of MUs change, also their firing characteristics change with age (Kamen et al., 1995). No consensus has been reached about this phenomenon. Some studies show that the firing frequency decreases and others show that the firing frequency becomes more variable, which may lead to a loss of motor control and force production (Connelly et al., 1999; Erim et al., 1999; Laidlaw et al., 2000; Roos et al., 1999; Soderberg et al., 1991). In addition, also the pattern of MU activation changes with age. As a basic rule, MUs are recruited according to their increasing size, with the larger MUs, innervated by the largest motoneurons, recruited only at the higher forces. This is called the Henneman’s size principle (Henneman and Olson, 1965; McPhedran et al., 1965). In elderly the recruitment thresholds of successively recruited MUs are lower and closer together. This contributed to greater muscle force fluctuations during sub-maximal contraction in older adults compared to young at the same relative force levels (Laidlaw et al., 2000). The changes that occur in the MUs with aging can lead to a reduction in strength and an impairment of the finger coordination (Hepple and Rice, 2016).

The above mentioned changes to both the muscle mass and neuromuscular properties of muscles may have an impact on the control of the hand and are expected to contribute to impaired hand versatility in elderly. Many of these changes have been found predominantly in the lower limbs. The changes of especially neural control of muscle regions corresponding to the different fingers of the extrinsic finger muscles have not been assessed before.

1.3.3. FDS tendons

Tendons are composed of connective tissue and concentrated collagen fibers. They are subjected to degenerative changes, since both the collagen and non-collagenous matrix components show qualitative and quantitative changes with aging. Interestingly, the absolute amount of collagen changes little, but the relative amount and the volume density increases due to the decrease in the proteoglycan-water
content (Ippolito et al., 1980; Kannus and Jozsa, 1991; Shadwick, 1990). The extracellular water content of a tendon declines from about 80% to 85% at birth to approximately 30 to 70% in elderly (Hess et al., 1989; Jarvinen et al., 1997). These changes have an effect on tendon gliding and stiffness.

During the aging process, the mechanical properties of collagen decrease due to an increase in the crosslinking of the tropocollagen molecules (Alnaqeeb et al., 1984; Nordin et al., 1989; O'Brien, 1992). This conversion to nonreducible crosslinks makes the tendon less compliant (Alnaqeeb et al., 1984; Viidik, 1979). The increase in collagen crosslinking alters the mechanical properties of the tendon and causes a decrease in ultimate strain (i.e. strain at failure), ultimate load (i.e. load at failure) and tensile strength (i.e. work done on the tendon until failure) (Tuite et al., 1997). However, an increase occurs in the mechanical stiffness of the tendon (Best et al., 1994; Viidik, 1979; Vogel, 1978). This increased stiffness of the collagen fibers also results in a decrease in the tensile strength of the connective tissue between tendons (Menard and Stanish, 1989).

Although several studies have shown that aging affects the properties of tendinous tissue, there are differences in the results. Some have shown that aging can result in stiffer, stronger and more resilient tendons (Shadwick, 1990), while other studies have shown the exact opposite (Clement et al., 1984; Khan et al., 2000). The inconsistency in these results could be explained by the use of different subject species, such as humans, rats and mice, and the age of the subjects. The effects of aging on the tendons of the extrinsic finger muscles have so far not been studied. As tendons transmit muscle forces to produce finger movements, the changes in mechanical properties with age must also affect finger movement control and, possibly, finger independence.

1.3.4. Finger independence

Studies have shown that with aging finger enslaving decreases during static finger pressing tasks, where the subjects were instructed to perform a maximum voluntary contraction (MVC) (Kapur et al., 2010; Oliveira et al., 2008; Shinohara et al., 2003a; Shinohara et al., 2003b; Yu et al., 2010). As one of the proposed functions of finger force enslaving is the stabilization of the total moment of force produced by all fingers together (Zatsiorsky et al., 2000), the lower enslaving in elderly may worsen the control of the rotational actions (Shim et al., 2007). From another perspective, the decrease in enslaving in the elderly is counterintuitive, as elderly often show impaired hand dexterity in daily life (Bennett and Castiello, 1994; Grabiner and Enoka, 1995; Marmon et al., 2011). No studies so far have found a mechanism for the decrease in
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finger enslaving. The changes that are known to occur with aging, such as the substitution of contractile tissue with connective tissue (Zimmerman et al., 1993) and motor unit enlargement (Vaillancourt et al., 2003), cannot explain the decreased enslaving. This suggest that other aspects might influence finger independence (Shinohara et al., 2003b). One study has looked at the relative muscle activation of both intrinsic and extrinsic muscles during finger pressing tasks and found that the force producing capacity of the intrinsic hand muscles show a greater decline than the extrinsic muscles (Shinohara et al., 2003a). However, no studies so far have looked at the changes that occur within the finger specific FDS muscles with aging.

2. Thesis Outline

The human hand has evolved to be able to perform skillful hand actions and is a fundamental attribute that enables us to grasp and manipulate objects and convey gestic information. In elderly a gradual decline in the quality of hand motor control is observed, which causes difficulties in performing everyday tasks such as grasping and fine handicraft. To understand the underlying cause for this decline in hand and finger movement, it is necessary to take all the different systems into consideration, such as muscles, tendons and central motor control, that undergo changes with aging and their mutual effect on one another. Although all these systems have often been studied separately as has been shown in the above mentioned papers, an integrative approach as can be found in this manuscript, i.e. studying both the finger movement mechanics and the hand motor drive, could clarify their effects on independent finger movement and the possible changes that may occur with aging.

The overall objectives of this thesis are to better understand finger independence during free finger flexion tasks, the underlying mechanisms that affect finger movement and to quantify age-related changes on hand motor control. Three main questions are addressed:

1.) Does the degree of finger independence change when the whole finger movement trajectory of multiple finger joints is taken into consideration in contrast to only measuring the total range of motion?
2.) How do the underlying mechanisms, such as neuromuscular control and tendon displacement, relate to finger independence?
3.) How does finger independence change with aging and what are the underlying mechanisms?

A main experimental set-up was used for all experiments described in this thesis (Fig. 4). Subjects were seated in a chair with their left forearm on a custom-made armrest

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with a palmar position of the hand of 45°. The main task tested was full range, active finger flexion until the tip of the finger(s) touched the palm of the hand and to then immediately extend the finger back. Finger kinematics were measured using the PowerGlove, a measurement device which uses inertial and magnetic sensors, to assess finger movement enslaving and the range of independent finger movement (Chapter 2). To study hand motor control, we used multi-channel surface EMG applying an electrode grid placed over the m. flexor digitorum superficialis (FDS) and the m extensor digitorum (ED) (Chapter 3). We thus achieved insight in the individual excitation of finger specific muscle bellies. Lastly, we used 2D ultrasonography and speckle tracking software to determine displacement and strain of the tendons inserted on the index, middle and ring fingers (Chapter 4).

In Chapter 2, the aim was to assess the extent of finger movement independence during full-range finger flexion, including all finger joints, in young subjects. Finger enslaving and the range of independent finger movement was studied during single and multi-finger movement tasks under two conditions: active finger flexion with all fingers free to move during the full trajectory of finger movement (= range of independent finger movement) and restrictive finger flexion, where only the instructed finger was free to move and the non-instructed fingers were restricted.

In Chapter 3, the activation and coactivation patterns of finger flexor and extensors muscles were studied in young subjects. To better understand how finger movement is controlled, the timing and muscle activation patterns of muscle regions within the FDS and ED muscles that could be associated with movements of individual fingers were measured using spatio-temporal sEMG recordings. To have more insight into finger independence and non-instructed finger movement, we also looked at the relationship between the enslaved finger movement and the corresponding muscle activation.

In Chapter 4, we investigated FDS tendon displacements of both the instructed and the neighboring, non-instructed fingers during single finger flexion movements. In Chapter 3, we found an increased activity of the antagonistic extensor digitorum (ED) muscle. Such agonistic-antagonistic coactivation is expected to result in forces exerted at the tendons and, consequently, stretching of the tendons. Thus, tendon displacements in the non-instructed fingers will probably not only be the result of finger and tendon movement, but also of tendon stretch. We thus also assessed whether tendon stretching was present in the tendon of non-instructed fingers. Tendon displacement was measured in young subjects during single finger flexion tasks again under the two conditions: active flexion of all finger joints with all fingers free to move and restrictive flexion where the instructed finger was free to move.
while the non-instructed fingers were restricted.

Following the results acquired on finger independence and some of its underlying mechanisms for young subjects in the previous experiments, we studied these aspects in the aging population in Chapter 5. To assess how aging affects finger movement control, we compared elderly and young subjects with respect to finger movement independence, neural control of extrinsic finger muscles and finger tendon displacements during single finger flexion.

Finally, in the general discussion presented in Chapter 6, the main results of both the young and elderly subjects are summarized and discussed. Furthermore, an outlook for future research and final conclusions are drawn.

**Figure 4: Visual impression of the thesis chapters.**