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Biomechanical Studies on Hand Function in Rehabilitation

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1. Introduction

Hand function requires interaction of muscles, tendons, bones, joints and nerves. The unique construction of the hand provides a wide range of important functions such as manipulation, sense of touch, communication and grip strength (Schieber and Santello 2004). The hand is used in many ways, and in many different situations in our daily lives; so injuries, diseases or deformities of the hand can affect our quality of life. Several of our most common injuries and diseases affect hand function. Therefore, it is very important to understand how healthy and diseased hands work in order to be able to design optimal rehabilitation strategies pursuant to hand injury or disease.

There are many different methods used today for evaluating hand and finger functions. One widely accepted method that provides an objective index of the hand and finger functions is hand force measurement (Balogun, Akomolafe et al. 1991; Innes 1999; Incel, Ceceli et al. 2002). There is also a potential for using modern non-invasive methods such as ultrasound and finger extension force measurements, but these have not been completely explored so far.

An important factor in developing grip force is the synergy between the flexor and extensor muscles. The extensor muscles are active when opening the hand, which is necessary for managing daily activities (Fransson and Winkel 1991). Even though the extensor muscles are important for optimal hand function, surprisingly little attention has been focused on these muscles. It has, however, been difficult to evaluate hand extension force, since there is no commercially available measurement instrument for finger extension force. In addition, because of the lack of a device to assess extension force, there is limited basic knowledge concerning different injuries and how diseases affect the static and dynamic forearm muscle architecture or/and muscle interaction.

Impaired grip ability in certain diseases such as Rheumatoid Arthritis (RA) could be caused by dysfunctional extensor muscles leading to inability to open the hand (Neurath and Stofft 1993; Vliet Vlieland, van der Wijk et al. 1996; Bielefeld and Neumann 2005; Fischer, Stubblefield et al. 2007). Deformities of the MCP-joints are common, and may lead to flexion contractures and ulnar drift of the fingers. Weak extensor muscles may play a role in the development of these hand deformities. Furthermore, knowledge concerning how the muscles are influenced by RA and the mechanism of muscle force impairments is not fully understood for RA patients. This group of patients would benefit from further hand/finger

evaluation methods for evaluation of rehabilitation and interventions. There is also a need for further knowledge of the dynamic action of skeletal muscle and the relation between muscle morphology and muscle force. The force that can be generated is dependent on the muscle architecture; these architectural parameters can be studied non-invasively with US. By using US it is possible to obtain detailed, dynamic information on the muscle architecture. In order to assess how disease influences muscle morphology and function, it is necessary to establish baseline knowledge concerning normal forearm muscles. The general aim of this book chapter was to further our knowledge about biomechanics of the hand, RA patient, non-invasive evaluation methods used for evaluation of rehabilitation interventions and muscle biomechanics will be further presented.

2. Biomechanics of the hand

It is important to understand the biomechanics of the hands and fingers as well as the muscle architecture and structure in order to develop new evaluation methods for finger extension force. The construction of the hand is quite complicated, including 29 joints, 27 bones and more than 30 muscles and tendons working together for range of motion (ROM), performing perception and force production.

2.1 The construction of the hand

The metacarpophalangeal (MCP) joints II-V are condyloid joints that allow for movement in two planes, flexion/extension or adduction/abduction. The ROM in the joints is approximately 30–40 degrees extension, 70–95 degrees flexion and 20 degrees adduction/abduction. Ligaments connect the bones and provide stability of the joints; in the hand there are numerous ligaments that stabilize the joints. To provide stability to the metacarpal bones, there are ligaments working in conjunction with a thick tissue located in the palm (the palmar aponeurosis). Muscles that control the hand and have their origin located near the elbow are called the extrinsic muscles. The tendons of these muscles cross the wrist and are attached to the bones of the hand. The large muscles that bend (flex) the fingers originate from the medial aspect of the elbow. The large muscles that straighten (extend) the fingers originate from the lateral aspect of the elbow. The extrinsic muscles are responsible for powerful grip ability. In addition to these large muscles, there are smaller muscles in the hand, intrinsic muscles, that flex, extend, abduct (move outwards) and adduct (move inwards). The agonist for extension in fingers II–V is the muscle extensor digitorum communis (EDC). This muscle originates at the lateral epicondyle of humerus; the muscle is connected to phalanges II–V by four tendons, which glide over the MCP-joints articulations. The tendons divide into three parts. The main part is attached to the extensor hood and two collateral ligaments are attached at the lateral and medial parts of the fingers. The extensor hood covers the whole phalange and is formed from the extensor digitorum tendon and fibrous tissue. The extension ability in the MCP-, proximal interphalangeal-, and distal interphalangeal joints are produced by EDC, interossei and lumbricales muscles (Smith 1996; Marieb 1997). Finger extension force is dependent on the wrist position. However, at the present time there is no consensus for the optimal wrist angle for finger extension force measurement. Researchers believe that a wrist position between 10-30 degrees is suitable for finger extension measurements (Li 2002).

2.2 Muscle force

The forces a muscle can produce depend on many factors such as the muscles' structure, muscle architecture, muscle-nerve interaction and physiological aspects. This thesis focuses mainly on how the muscle structure, at macro level, affects the forces produced. A brief overview of the micro architecture level and muscle control is described in this chapter.

The skeletal muscles have four behavioral properties, extensibility, elasticity, irritability and the ability to develop tension. Extensibility and elasticity provide muscles the ability to stretch or to increase in length and to return to normal length after stretching and these properties provide a smooth transmission of tension from muscle to the bones. The muscle's ability to respond to stimuli, irritability, provides the capability to develop tension. The tension that muscles provide has also been referred to as contraction, or the contractile component of muscle function. The tension that a muscle can develop affects the magnitude of the force generated, the speed, and length of time that the force is maintained; all these parameters are influenced by the muscle architecture and function of the particular muscle. The manner in which the muscles are constructed and controlled contributes to muscle force production. The force that a muscle generates is also related to the velocity of muscle shortening, such as the force-velocity relationship, length-tension relationship, stretch-shortening cycle and electromechanical delay (Wickiewicz, Roy et al. 1984; Brand 1993; Fitts and Widrick 1996; Kanehisa, Ikegawa et al. 1997; Debicki, Gribble et al. 2004; Hopkins, Feland et al. 2007).

2.2.1 Macro-architecture

Muscle architecture has been studied by muscle-imaging techniques such as magnetic resonance imaging and ultrasound (US), and research has shown that there are numerous variations in the muscle architecture (i.e. fibre length, pennation angle, cross-sectional area (CSA), muscle volume etc.) within and between species. The architecture of a skeletal muscle is the macroscopic arrangement of the muscle fibres. These are considered relative to the axis of force generated (Otten 1988; Blazevich and Sharp 2005). The arrangements of muscle fibres affect the strength of muscular contraction and the ROM which a muscle group can move a body segment. It is important to understand the impact of muscle architecture parameters in order to design effective interventions for disease, injury rehabilitation, as well as for athletic training and exercise, especially considering the results of adaptation to physical training. The pennation angle is the angle between the muscle fibre and the force generating axis (Figure 1). Early researchers have reported greater pennation angles in subjects that practice weight training compared to untrained subjects. It has been claimed that increase in pennation angle is biomechanically important since more tissue can attach to a given area of tendon, and slower rotation of the muscle fibre during contraction is possible through a greater displacement of the tendon, thus generating more force (Aagaard, Andersen et al. 2001; Kawakami, Akima et al. 2001).

Fascicle length (muscle fibre) can be of importance for the biomechanics of the muscles, the change in fascicle length has been reported to have impact on high-speed force generation (Fukunaga, Ichinose et al. 1997). The fascicles containing a greater number of sarcomeres in series and generate force over longer ranges of motion and longer fibres also possess greater shortening speeds. From experimental studies, it has been claimed that the physiological cross-sectional area (PCSA) of a muscle is the only architectural parameter that is directly proportional to the maximum tetanic tension generated by the muscle. Theoretically, the

PCSA represents the sum of all CSA of the muscle fibres inside the muscle. The design of the muscles in terms of pennation angle, fibre length and PCSA reflects the muscles' capacity to develop force. Although each muscle is unique in architectural design, a number of generalizations have been made on the lower extremity muscles. For example quadriceps muscles are designed with high pennation angles, large PCSA and short muscle fibres, and this design is suitable for large force production. The same design pattern can be observed in the upper extremity, and the flexor muscles structure predicts that they generate almost twice the force as the extensor muscles (Lieber and Friden 2000). To summarize: the research about muscle architecture and adaptation to speed and strength exercises shows that muscle architecture is plastic and can respond to exercise, although more research is required to fully understand the impact of varying methods of strength and speed training. To fully understand the adaptation of muscle architecture to all forms of interventions would require a formidable research effort. Surprisingly little research has described changes of muscle architecture when aging, despite that aging is associated with significant sarcopenia.
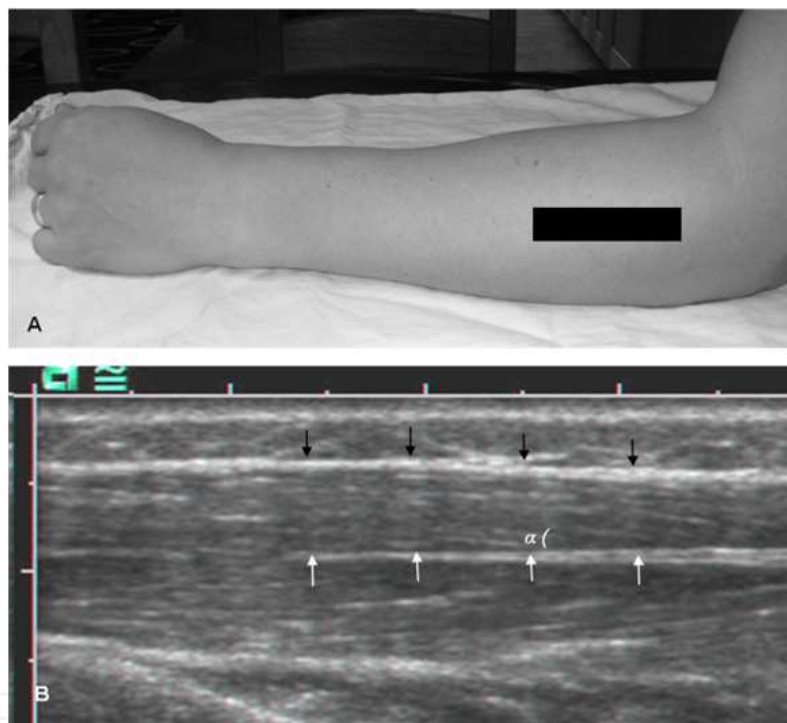

Fig. 1. (A) The black rectangle shows the position of the US probe during pennation angle measurements of the m.EDC. (B) The longitudinal US image showing the superficial aponeurosis (black arrows), the deep aponeurosis (white arrows) and the pennation angle (α). ©Sofia Brorsson

Previous research has claimed that pennation angle and fascicle length were significantly smaller in older than younger individuals in some muscles such as m. soleus, m. gastrocnemius medialis and lateralis (Kubo, Kanehisa et al. 2003; Narici, Maganaris et al. 2003; Morse, Thom et al. 2005), but there were no age related changes in m. triceps brachii and m. gastrocnemius medialis concerning pennation angles for women (Kubo, Kanehisa et al. 2003).Furthermore, little research has been done concerning how muscle architecture adapts to disuse or diseased muscles, which is very important from a rehabilitation perspective. Kawakami et al. (2000) investigated changes in the muscle parameters fascicle

length, pennation angle and CSA in m.triceps brachii and m. vastus lateralis after 20 days of bed rest. They found no significant changes in fascicle length and pennation angle even though there was a significant reduction of the CSA (Kawakami, Muraoka et al.2000). Other researchers have reported decreased muscle size, muscle strength and decreased pennation angles after bed rest (Akima, Kuno et al.1997; Narici and Cerretelli 1998; Kawakami, Akima et al. 2001). It has been claimed that one explanation for the different adaptations of muscle architecture in different disused muscles (due to bed rest) is that the changes depends on the individual muscle actions.

2.2.2 Micro-architecture

The skeletal muscles have a wide range of variations in size, shape, and arrangement of fibres. Skeletal muscles are composed of muscle fibres that are bundled together in fascicles, the fascicles are composed of about 200 muscle fibres. Each muscle fibre is surrounded by the endomysium, which is connected to muscle fascia and tendons. The muscle fibres are formed by myofilaments, comprised of myofibrils. A contractile myofibril is composed of units, sarcomeres (Smith 1996; Marieb 1997). By using electron microscopy researchers have observed the muscle structure (ultra-structure) and structures such as sarcomeres, actin and myosin were analysed (Alberts 2002). These structures have become the basis of the theory of sliding filaments during muscle contraction and later to the Cross-bridge theory, which has become the accepted paradigm for muscle force production (Huxley 1954; Huxley 1957; Huxley and Simmons 1971).

2.2.3 Muscle control

Muscles allow us to move our joints, to apply force and to interact with our world through action. Muscles are important for us because they have the unique ability to shorten, and to do that with enough force to perform movements. Muscle fibres are arranged into functional groups; there, all fibres are innervated by one single motor neuron; these groups are called motor units. Movements that are precisely controlled such as the finger movements are produced by motor units with small numbers of fibres (Kandel, Schwartz et al. 1991). When a muscle fibre is activated by a motor nerve impulse, the actin and myosin filaments in the sarcomere connect strongly to each other, pulling the filaments together. Sarcomeres are arranged in long chains that build up the muscle fibre, so when the sarcomeres contract, become shorter, the whole fibre becomes shorter. To be able to produce force the muscle must be innervated by a motor neuron, and the excitation-contraction coupling is along the whole fibre length simultaneously through the T-tubule system. This leads to rapid release of calcium ions from the sarcoplasmic reticulum. When the contraction signal ends, the calcium is driven back to the sarcoplasmic reticulum through ATP-driven calcium pumps (Kandel, Schwartz et al. 1991). Increase in neuromuscular function and muscle strength is attained when the load intensity exceeds that of the normal daily activity of the individual muscles (Hellebrandt and Houtz 1956; Karlsson, Komi et al. 1979). Increase in muscle performance at the beginning of strength training can be explained by physiological and neural adaptation, such as effective recruitment of motor units and reduction of inhibitory inputs of the alpha motor neurons (Hakkinen, Malkia et al. 1997). Several researchers have reported that muscle hypertrophy occurs after 6–8 weeks of strength training and that a certain level of muscle strength is needed to prevent a decline in functional capacity (Nygard, Luopajarvi et al. 1988; Sale 1988; Kannus, Jozsa et al. 1992). Inactivity or decrease

in physical activity leads to loss of muscle strength and a decrease in neuromuscular performance, this has been observed for patients with arthritis (Hakkinen, Hannonen et al. 1995). Some researcher claim that, during the early phase, muscle force production after exercise is more related to improved innervations than increased CSA (Blazevich, Gill et al. 2007).

3. Non-invasive evaluation methods in rehabilitation

In this thesis, the effect of both the static and dynamic muscle architecture and the ability to produce force is studied in the extensor muscle EDC in healthy subjects and RA patients; either as physical performance or self-reported function. There are different evaluation methods available to evaluate muscle architecture, force production and hand function in rehabilitation.

3.1 Grip force measurements

Hand force is an important factor for determining the efficiency of interventions such as physiotherapy and hand surgery. Hand force/grip strength is widely accepted as providing an objective measure of the hand function (Balogun, Akomolafe et al. 1991; Incel, Ceceli et al. 2002) and measurements of grip force have been used to evaluate patients with upper extremity dysfunction. However, measurements have mainly been made of the flexion force and pinch force. Even though flexion forces represent only 14 % and tripod pinch grip only 10 % of all daily hand grip activity (Adams, Burridge et al. 2004). Surprisingly little measurements have been made of the finger extension force, despite the fact that extension force is important in developing grip force. Furthermore, it has been difficult to evaluate hand extension force impairment, since no commercially available measurement instrument for finger extension force exists. Some research instruments have been designed. However they are complicated, with little clinical potential and do not have the ability to measure both whole hand extension force and single finger extension forces as the new force measurement device, EX-it, has (Brorsson 2008 a, Kilgore, Lauer et al. 1998; da Silva 2002; Li, Pfaeffle et al. 2003). Hand grip measurements have been seen to be a responsive measure in relation to hand pain and correlate well with patients' overall opinion of their hand ability; these measurements provide a quick evaluation of patient's progress throughout treatment (Incel, Ceceli et al. 2002; Adams, Burridge et al. 2004). Grip force is influenced by many factors including fatigue, time of day, hand dominance, pain, sex, age and restricted motion. Interestingly, the synergistic action of flexor and extensor muscles is an important factor for grip force production (Richards, Olson et al. 1996; Incel, Ceceli et al. 2002). It is widely accepted that grip and pinch force measurements provide an objective index of the functional integrity of the upper extremity. Today there are devices for measuring some grips, such as Jamar™, Grippit™, MIE digital power and pinch grip analyser™ and Pinchmeter ™ (Nordenskiold and Grimby 1993; Lagerstrom and Nordgren 1998; Mitsionis, Pakos et al. 2008). Severe weaknesses in RA patients' grip forces have been reported by several authors. Nordenskiöld et al. (1993), reported reduced flexion force for RA women compared to healthy controls using the Grippit device. Furthermore, Nordenskiöld (1997) reported a relationship between significant grip force and daily activities (Nordenskiold and Grimby 1993; Nordenskiold 1997). The activity limitations in relation to grip force and sex after 3 years of RA has been claimed to be lower for women than for men. The authors concluded that this result may be explained by reduced grip force rather than sex (Thyberg,

Hass et al. 2005). Fraser et al. (1999) reported weakness in three different grip types using an MIE digital power and pinch grip analyser. They measured flexion force, pinch force and tripod force. They also measured forearm parameters which they expected to be relevant for producing forces, such as hand and forearm volume. They could however not find any significant differences between healthy and RA parameters (Fraser, Vallow et al. 1999). Buljina et al. (2001) reported the effectiveness of hand therapy for RA patients. They evaluated grip strength with the measuring device called Jamar 1113 (Sammons-Preston, Jackson, MI), then they analysed the tip-to-tip pinch, palmar pinch, key pinch, range of motions in the MCP-joints while pain in the hands was measured by a visual analog scale (VAS). They reported the effectiveness of therapy and that the RA patients significantly increased their hand force (Buljina, Taljanovic et al. 2001). Jones et al. (1991) reported that RA patients hand force was 75 % lower than healthy subjects (Jones, Hanly et al. 1991). Even though hand exercises are used frequently for keeping and preventing loss of grip force for RA patients, only few studies have evaluated the result of grip improvement (Hoenig, Groff et al. 1993). Adams et al. (2004) reported flexion and tripod force recorded by an MIE digital grip analyser, hand function was evaluated with the Grip ability test (GAT) and the patient's questionnaire Disability Arm Shoulder Hand (DASH). They concluded that grip force was significantly correlated to self-reported assessment and hand function (Adams, Burridge et al. 2004). Brorsson et al. (2008 a,b) showed that the extension force was significantly reduced in the RA group (men, $p < 0.05$, and women $p < 0.001$) compared to the control group. Furthermore, they showed that there was a significant difference between the finger extension force for healthy men and women ($p < 0.001$), the finger extension force and flexion force in the dominant hand for healthy subjects and RA patients are presented in Figure 2.
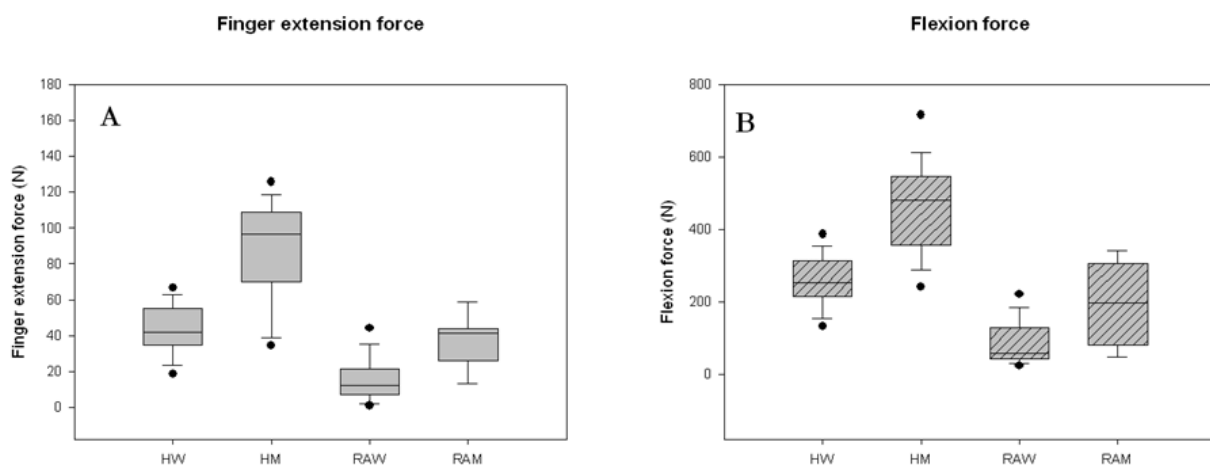

Fig. 2. (A) Finger extension force in dominant-hand. (B) Flexion force in dominant-hand. The box-plots represent healthy women (HW), healthy men (HM), women with RA (RAW) and men with RA (RAM). The results are from participants in all papers (n=80 HW, n=47 HM, n=65 RAW and n=12 RAM).

3.2 Ultrasound examination in skeletal muscle architechture

Ultrasound technology provides new and exciting possibilities to non-invasively access physiological mechanisms inside the living body, both at rest and during muscle contraction. Ultrasonic devices collect sound waves that are emitted by a probe after

reflecting off the body's internal tissues; this provides detailed images of the body structures. The recent developments of the probes have enabled the use of US to examine the joint and surrounding soft tissues such as the muscles. The increasing interest for US among rheumatologists contributes to the understanding of the natural history of rheumatic diseases, and US is today important in the early diagnosis of RA (Kane, Balint et al. 2004; Grassi, Salaffi et al. 2005) . US has been used in several studies to provide *in vivo* information about the muscle architecture of different muscles. Zheng et al. (2006) combined US with surface electromyography for evaluating changes in muscle architecture after using prosthetics (Zheng, Chan et al. 2006). US has also been used to study the differences between men and women regarding muscle parameters such as muscle pennation angles and muscle fascicle length (Kubo, Kanehisa et al. 2003). US allows for dynamic studies of muscle architecture, Fukunaga et al. (1997) have developed a method to study the fascicle length during contraction (Fukunaga, Ichinose et al. 1997). Furthermore, US has been used to analyse the muscle architecture's response to age, the authors concluded that some muscles in the lower extremities decreased in thickness with aging but the fascicle length did not decrees with aging (Kubo, Kanehisa et al. 2003). Loss of muscle mass with aging has been reported to be greater in the lower extremities than in the upper extremities. Decreases in CSA of the muscles have been reported to be 25-33 % lower in young compared to elderly adults (Narici, Maganaris et al. 2003). However, several researchers have reported decreased muscle strength but not decreased CSA, so the force, expressed per unit of muscle CSA, has been reduced in older individuals (Young 1984; Macaluso, Nimmo et al. 2002; Narici, Maganaris et al. 2003). US has been applied to the rotator cuff muscles to analyse the dynamic contraction pattern of these muscles to confirm the neuromuscular intensity (Boehm, Kirschner et al. 2005). Fukunaga et al. (1997) used US to measure muscle architecture and function in human muscles. They pointed out that the use of cadavers for studies of architecture and modelling of muscle functions would result in inaccurate and, in some cases, misleading results (Fukunaga, Kawakami et al. 1997). Aagaard et al. (2001) used US to measure the response to strength training and the changes in muscle architecture. They concluded that the quadriceps muscle increased both its CSA and the pennation angle after heavy resistance training (Aagaard, Andersen et al. 2001). Rutherford and Jones (1992) did not find any increased pennation angles after resistance training, even though they reported increased CSA and muscle force in the quadriceps muscle (Rutherford and Jones 1992). Brorsson et al. (2008) showed that there was a significant difference between the muscle anatomy of healthy men and women. The results of the ultrasound measurements and the differences in muscle architecture parameters between healthy men and women, and healthy women and RA women are summarised in Table 1.

The overall shape changes in muscle CSA during contraction were more pronounced for men than for women, ($p < 0.01$). US studies have also been performed on human skeletal muscles to explore the changes in muscle architecture that occur during dynamic contractions. The authors found that at a constant joint angle, the fascicle length and the pennation angles changed significantly during muscle contraction (Reeves and Narici 2003).

3.3 Function test evaluation, patients' questionnaires and visual analogue scale in hand rehabilitation

The Grip Ability Test (GAT) is designed for individuals with RA; it measures ADL ability. The test is based on three items chosen to represent different daily grip types. The test is performed following a standardized protocol consisted of three items: to put a "sleeve"

(Flexigrip™ stocking) on their non-dominant hand, place a paper clip on an envelope and pour 200 ml into a cup from a 1 litre water jug. GAT is a reliable, valid and sensitive ADL test (Dellhag and Bjelle 1995). Hand function has been assessed by GAT for measuring grip ability and activity limitations in several studies. Dellhag et al. (1992) reported that RA patients have improved their hand function after just 4 weeks of hand exercise (Dellhag, Wollersjo et al. 1992). Bjork et al. (2007) showed significant differences in activity limitations between healthy controls and RA patients in there study using GAT (Bjork, Thyberg et al. 2007). The relationship between self-reported upper limb function and grip ability was studied in an early rheumatoid population by Adams et al. (2004). They reported correlation between GAT and the questioner DASH (Adams, Burridge et al. 2004). Dellhag et al. (2001) reported in their study that patients with RA that have good hand function, low GAT score, displayed normal or increased safety margin during precision grip-lift compared to healthy controls (Dellhag, Hosseini et al. 2001).

Muscle parameter	Healthy men (n=20)	Healthy women (n=20)	RA women (n=20)
Thickness (cm)	1.2 (1.0-1.6)**	1.0 (0.7-1.2)*	0.8 (0.6-1.2)
CSA (cm²)	2.5 (1.6-3.3)**	1.8 (1.0-2.6)*	1.7 (0.4-2.5)
Fascicle length (cm)	6.6 (3.8-9.5)**	4.8 (3.9-7.0)*	4.4 (2.4-6.7)
Pennation angle (degree)	6.7 (3.3-8.5)*	5.3 (4.0-8.5)	5.6 (3.8-6.5)
Volume (cm³)	27.5 (18.6-43.1)**	16.7 (9.7-28.9)**	12.5 (3.1-23.5)

Muscle parameters are presented as median (range)
*p < 0.05, ** p < 0.01 (significant differences between healthy men – healthy women and between healthy women – RA women).

Table 1. Muscle architechture of EDC

Self-administered questionnaires are recommended for evaluating functional disability from the patients' perspective (Guillemin 2000; Liang 2000). The hand function is affected early on in RA and can be evaluated with different methods. One widely used selfadministrated extremity-specific questionnaire is the Disability of the Arm, Shoulder and Hand (DASH) that is been reliable and validated for assessing upper limb functional ability in the RA population (Atroshi, Gummesson et al. 2000). DASH has been used for evaluating the effectiveness of patient-oriented hand rehabilitation programmes, and has shown significant differences between two rehabilitation programmes and surgery (Gummesson, Atroshi et al. 2003; Harth, Germann et al. 2008). Furthermore, DASH has been used by Solem et al. (2006) for evaluation of long-term results of arthrodesis (Solem, Berg et al. 2006). Adams et al. (2004) showed in their study that DASH was useful to evaluate the relationship between upper limb functional ability and structural hand impairment (Adams, Burridge et al. 2004). Another commonly used generic questionnaire for evaluating functional disability in people is the Short Form 36-item Health Survey (SF-36), there a validated Swedish version has been developed (Sullivan, Karlsson et al. 1995). Generic healthy status measurements are commonly used for evaluation of RA patients. SF-36 has been used to detect the treatment effect in the study outcomes. Furthermore, use of SF-36 permits comparisons of physical and mental aspects in the RA population, as well as comparison between patients with RA, other patients groups and the general population (Tugwell, Idzerda et al. 2007). SF-36 has been used in several studies to evaluate the clinical outcome and quality of life after arthroplasty,

and concluded the health status and the overall physical functions with significant improvements for RA patients (Angst, John et al. 2005; Ringen, Dagfinrud et al. 2008; Uhlig, Heiberg et al. 2008).

Visual analog scale (VAS) pain is a method frequently used to measure perceived pain level and the impact that high pain levels have on functional disability. Decreased functional ability in patients with RA has been reported correlated with on disease activity, disease duration, age, grip force and high pain level (Oken, Batur et al. 2008). Hand disabilities were detected in 81 % of RA patients and strongly correlated to pain level, grip force and clinical and laboratory activity. Female RA patients have reported more pain and worse disability than men (Bodur, Yilmaz et al. 2006; Hakkinen, Kautiainen et al. 2006). Brorsson et al. (2008) reported that neither the RA group nor the controls showed any significant improvement in DASH score after 6 weeks of hand exercise therapy. However, after 12 weeks of hand exercise the RA group showed a significant improvement in the DASH score, while there was still no improvement in the control group. Neither group showed any significant improvement in the SF-36 score after the hand exercises (Figure 3). However, some of the RA patients reported "tiredness" in their hands after the exercise.

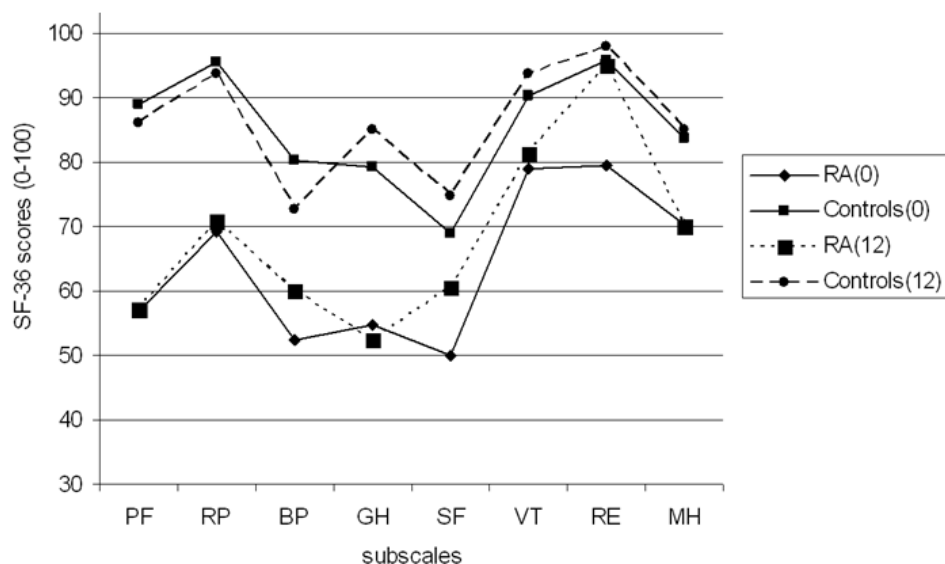The exercises caused no significant change in the pain level (Table 2).

Fig. 3. SF-36 score pre- and post hand exercise therapy

Results of the SF-36 questionnaire, before (0) and after 12 weeks (12), of hand exercises. The scale is 0–100, from worst to best. The questionnaire is designed for measuring the generic health in the general population but is also useful for different patient groups. SF-36 is divided into eight health profiles scales; physical function (PF), role physical (RP), bodily pain (BP), general health (GH), vitality (VT), social functioning (SF), role emotional (RE) and mental health (MH). All dimensions are independent of each other.

4. The hand in rheumatoid arthritis

RA is our most frequent autoimmune inflammatory disease, with prevalence of nearly 1 %. RA is found throughout the world and affects all ethnic groups. It may strike at any age, but its prevalence increases with age; the peak incidence being between the fourth and sixth decades. The prevalence is about 2½ times higher in women than in men. The onset of symptoms

usually involves symmetrical joints in hand and feet, but RA is a systemic disease and might affect any organ such as vessels, pleura or skin. There is often involvement of multiple joints and surrounding tissues. It's estimated that 80-90 % of the RA patients suffer from decreased hand function (Maini 1998; O'Brien, Jones et al. 2006). The hand in most patients may develop some typical pattern of deformity. These deformities are influenced by several factors, such as inflammation in the joint with distension of the joint capsule and ligament attenuation. Inflammation in and around tendons might distend tendon sheaths and cause tendon ruptures. The influence of disease by the characteristic MCP-joint deformity of ulnar drift (Figure 4), results of local joint forces (Smith and Kaplan 1967; McMaster 1972; Tan, Tanner et al. 2003; Bielefeld and Neumann 2005). Muscle involvement can lead to weakness and contractures. RA patients are frequently affected by pain, weakness and restricted mobility: the deformities of the hand, in various degrees, leads to limitation in activities of daily living (ADL) (Chung, Kotsis et al. 2004; Mengshoel and Slungaard 2005; Masiero, Boniolo et al. 2007).

	Week	RA group (n=18)			Control group (n=18)	
		Median	Range		Median	Range
GAT	0	19.8	16.5 – 51.6		13.4	8.9 – 16.9
	6	16.8	14.4 – 40.0**		11.5	6.9 – 15.8**
	12	16.1	12.1 – 30.2**		10.3	7.7 – 14.5**
DASH	0	37.3	8.8 – 62.5		2.5	0.0 – 16.3
	6	37.5	5.8 – 75.0		2.1	0.0 – 17.5
	12	39.2	6.7 – 47.5*		5.0	0.0 – 15.0
VAS	0	1.5	0.0 – 6.0		0.0	0.0 – 2.0
	6	2.5	0.0 – 7.0		0.0	0.0 – 2.0
	12	2.0	0.0 – 7.0		0.0	0.0 – 2.0

Median values of hand function tests before (week 0) and after 6 and 12 weeks of hand exercise. Median and range are given for the grip ability test (GAT), disability, of arm shoulder and hand questionnaire (DASH) and reported pain level (VAS). Number of participants (n=#)
$*p < 0.05$, $**p < 0.01$

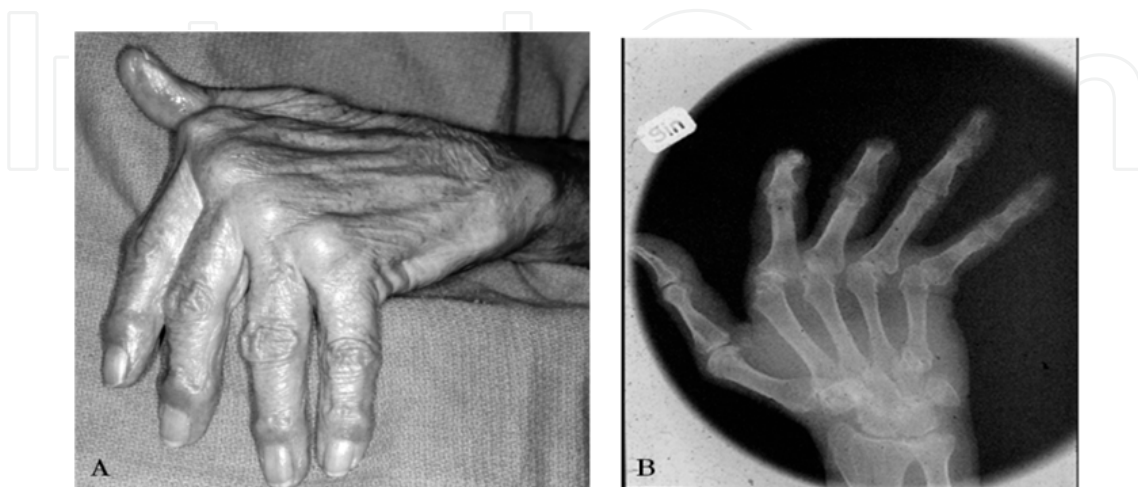Table 2. Hand function evaluations before and after hand exercise.

Fig. 4. The hand in most patients may develop some typical pattern of deformity; these images show the characteristic MCP-joint deformity of ulnar drift. ©Sofia Brorsson

The exact cause of RA is still unknown, however genetic, hormonal and environment factors have been reported to be involved in autoimmune diseases such as RA (Ollier and MacGregor 1995; Reckner Olsson, Skogh et al. 2001; Tengstrand, Ahlmen et al. 2004). Diagnosis of RA are based on ACR criteria which include; pain and swelling in at least three joint areas, symmetrical presentation, early morning joint stiffness for more than 1 hour, involvement of MCP joint or PIP joint or wrists, subcutaneous nodules, positive rheumatoid factor and radiological evidence of erosions. At least four of these signs or symptoms should be present for six weeks (Arnett, Edworthy et al. 1988). Pain and tenderness of the joints are well described and documented (Pearl and Hentz 1993), but there is less knowledge concerning how the muscles are influenced by the disease. The most common histological findings in RA are the pronounced muscle atrophy and nodular myositis. Magyar et al. (1973) observed changes in the muscles consistent with denervation using electron microscopy. These authors showed that the muscle changes might be due to a direct involvement of the neuromuscular system and that the pathological changes affect the contractile element in the muscles (Magyar, Talerman et al. 1973). An important part of hand function is based on the function of the muscles which are involved in finger and wrist motion and the ability to develop grip force. RA patients often report that they feel weakness, particularly when performing flexion force. There are several possible reasons for this weakness such as reduction in muscle fibre diameter, direct involvement of inflammatory processes in the muscle, joint deformity influencing muscle function and pain (Haslock, Wright et al. 1970; Leading 1984; Bruce, Newton et al. 1989). The muscle structure (ultra-structure) and changes in rheumatoid arthritis have been recognised pathologically and clinically. Although electron microscopy is valuable in investigating human skeletal muscle both in normal and RA muscles, only a few data sources document muscle ultra-structural alterations in RA patients (Haslock, Wright et al. 1970; Magyar, Talerman et al. 1973; Wollheim 2006). Furthermore, a non-invasive study on muscle architecture in RA patients appears to be poorly investigated.

4.1 Rehabilitation and intervention of the Rheumatoid Arthritis hand

Treatment of RA is focused on reducing the inflammatory activity by medication, rehabilitation and surgery (Stenstrom and Minor 2003). New disease modifying drugs for RA patients administered early after onset have made it possible for people with this disease to stay more active and more fit than 10-20 years ago (Pincus, Ferraccioli et al. 2002). Today's treatment options to increase hand function for RA patients include electrotherapy, injection therapy, manual therapy and traditional exercise prescription, but the evidence base for treatments remains weak, particularly when focusing on the hand (Weiss, Moore et al. 2004; Plasqui 2008). In 1974, Lee et al. reported in their study that immobilization and/or physical rest were beneficial in the treatment of RA, leading to a decrease in pain and joint swelling (Lee, Kennedy et al. 1974). Other groups have reported that the forces involved in using the hand lead to joint erosion and increased deformities (Ellison, Flatt et al. 1971; Kemble 1977). Despite earlier fear of aggravating symptoms, there is now scientific evidence showing that various forms of exercise are both safe and beneficial (Stenstrom and Minor 2003). However, comparatively little research has evaluated the evidence for the benefits of hand exercise in RA (O'Brien, Jones et al. 2006). Recently reviewed effectiveness on hand exercise therapy in RA patients showed that only nine eligible studies have incorporated hand exercise therapy as part of the intervention (Chadwick 2004; Wessel 2004). Hoening et al. (1993) showed in

their study that a home hand exercise program was effective for increasing the grip force in the RA hand (Hoenig, Groff et al. 1993). Intensive hand exercise has previously been reported to be effective for improving grip- and pinch force for RA patients (Ronningen and Kjeken 2008). Brorsson et al. (2008) have showed that a regular home exercise programme for the RA hand, evaluated with force measurements, ultrasound examination, function test and patients questionnaires (Figure 5), is beneficial for grip (flexion and extension) force production. Furthermore, they reported that hand exercise improves the relation between flexion and extension forces as well as improved hand function. They also reported improved flexion and extension force for the RA patients after 12-weeks of hand exercise (Figure 6).
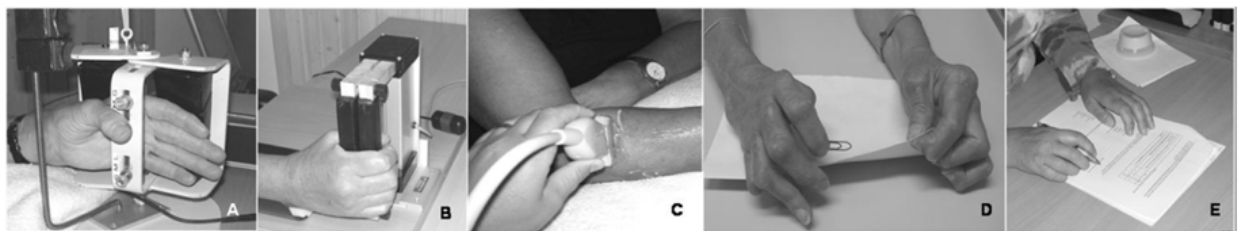
Fig. 5. The total study period was 18 weeks of home hand exercise, divided into 6-week periods. Baseline values were determined at week 0 (Occasion I) and 6 (Occasion II). Thereafter, the hand exercise programme was started, and the effects were measured after 6 weeks (Occasion III) and 12 weeks (Occasion IV). Evaluation methods used: (A) finger extension force measurements (EX-it), (B) Flexion force measurements (Grippit™), (C) US examination of the EDC muscle, (D) grip ability test, and (E) questionnaires.
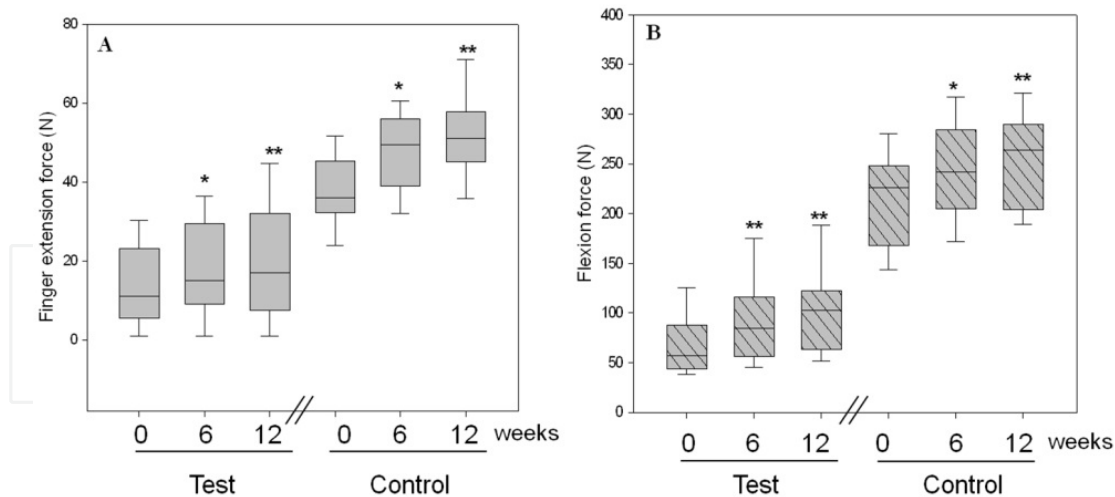

Fig. 6. Illustrates the finger extension force (A) and flexion force (B) in the two groups of participants in paper IV after 6 and 12 weeks of hand exercise. Both groups show significant improvement after 6 and 12 weeks (* $p < 0.05$, **$p < 0.01$).

Hand surgery has been regarded as beneficial for some patients with RA. Arthroplastic procedures of the wrist and fingers have been performed since 1960. An increasing number of patients with RA receive joint replacements in the MCP joints of the hand. The purpose of these operations is to improve the patients' extension ability, extension force, and hand

function as well as reduce pain (Weiss, Moore et al. 2004). At present, when the outcome of surgery is evaluated, it is impossible to objectively test if the patients' finger extension force has been improved or not, since no force measurement device for finger extension force is commercially available. It is necessary to find methods to objectively measure hand function in order to be able to evaluate the functional impairment, as well as the results of therapeutic interventions i.e. surgery or physical therapy.

5. Conclusion

To further our understanding of hand function, and specifically the extensor muscles' function and ability to produce force in rehabilitation, this book chapter describes the development and results of new non-invasive methods, a new finger extension force measurement device, EX-it, and an ultrasound imaging method (Brorsson et al. 2008 a,b). Furthermore, the results of this book chapter show that finger extension force measurements and ultrasound are effective methods for evaluating improvement after the intervention hand exercise. The effect of hand exercise on the extensor muscles could be objectively evaluated with EX-it and ultrasonic imaging. This chapter also reported the usefulness of short-term hand exercise for patients with RA and that a home exercise programme can enhance hand function.

Various methods can be used to study muscle architecture, including ultrasound, magnetic resonance imaging (Juul-Kristensen, Bojsen-Moller et al. 2000; Aagaard, Andersen et al. 2001) and laser diffraction. Laser diffraction is an invasive technique, while magnetic resonance imaging is only suitable for static measurements. Ultrasound, on the other hand, is non-invasive and clearly shows the movement of the muscle (Fukunaga, Ichinose et al. 1997). It is also harmless, can be repeated and offers the possibility of dynamic examinations. The limitations with US are the quality of the examinations, which are dependent on the investigator's ability to reproduce the imaging conditions (measurements), to find correct landmarks in both transverse and longitudinal direction and standardise the procedures. Ultrasound has been shown to be a highly valuable tool to assess *in vivo* muscle architecture for studying muscle function and relationships between muscle force and muscle size (Maughan, Watson et al. 1984; Hakkinen and Keskinen 1989; Kawakami, Abe et al. 1993; Fukunaga, Kawakami et al. 1997).

In rheumatoid arthritis, impaired finger extension is a common symptom; differences in extension muscle force capacity as well as in muscle architectural parameters, between normal and RA muscles are reported. Earlier studies have reported that RA patients also have weaker grip, pinch and tripod force than healthy controls, and it has been suggested that force assessment could be used as an accurate indicator of upper limb ability and that grip force (i.e. flexion and pinch force) should be included in the evaluation and follow-up of the patients with RA in hand rehabilitation units (Helliwell and Jackson 1994; Fraser, Vallow et al. 1999; Adams, Burridge et al. 2004; Bodur, Yilmaz et al. 2006). The decrease in force capacity could be explained by a direct effect of the disease on muscle function, disuse or impaired neuromuscular transmission, or different medications, but the decrease could also be due to the fact that the RA patients experienced more pain than the healthy subjects, a situation which could influence their maximal muscle exertion. Loss of hand grip force has been shown to result from pain, or fear of pain, or mechanical malfunction (Fraser, Vallow et al. 1999).

Ultrasound is a non-invasive and harmless method that can be used to visualise functionally important muscle parameters dynamically. Finger extension control is one of the most difficult motions to regain after disease/injury and is also very important for prehensile activities (Cauraugh, Light et al. 2000). Since both EX-it and ultrasound have been shown to be sensitive in their evaluation of hand exercise, it can be expected that these methods can be used to evaluate other interventions, such as surgical procedures, physiotherapy and/or pharmacological treatment. With these new methods, arthroplastic interventions in the MCP-joints of the fingers can objectively be evaluated. In a longer perspective it may be possible to establish more efficient rehabilitation programmes for RA patients. Furthermore, force measurements are a quick and easy measure of hand impairment and function, and are useful when evaluating hand status. EX-it in combination with other non-invasive evaluation methods (i.e.grip ability tests and health assessment questionnaires) will provide more information on hand function. Patients with rheumatoid arthritis suffer from a variety of functional deficiencies, of which impaired muscle function is a serious one. There is a recent trend towards the use of non-invasive methods in studying disease-specific changes, such as magnetic resonance imaging and ultrasound. Increased knowledge concerning muscle morphology and function in RA will allow better diagnosis and evaluation of interventions, such as surgical procedures, physiotherapy and/or pharmacological treatment. In a longer perspective it may be possible to establish a more efficient rehabilitation programme for RA patients. If combined with functional and clinical measures of disability, information on muscle architecture could then be used as an objective tool in the assessment of hand function after physical therapy and hand surgery.

In this thesis no negative effects of EX-it, ultrasound or the exercise programme on self reported pain level were reported in the RA group. It is possible that RA patients need continuous exercise to prevent loss of muscle strength and to improve the performance of activities of daily living (Stenstrom 1994; Hakkinen, Malkia et al. 1997; O'Brien, Jones et al. 2006; Masiero, Boniolo et al. 2007). However, the response to exercise from RA patients must be further evaluated to find out if longer exercise period can obliterate the differences between healthy and rheumatoid arthritis muscle strength and function; or to find out if these differences depend on a disease-specific effect on the rheumatoid arthritis muscles.

5.1 Future implications

Several questions have arisen during writing this book chapter and performed research in this area and require further research. It would be of interest to analyse how EDC responds during contraction at different locations of the muscle. Brorsson et al. (2008 a,b, 2009)reported that the inter muscle movement pattern in the muscle was observed, but were unable to measure it with the methods used for this thesis. Further knowledge about *in vivo* muscle pattern could provide information about the muscle as well as the elastic characteristics of the aponeurosis and tendon.

- Is it possible that the EDC, a muscle designed for precision tasks and grip control rather than force exertion, is constructed differently from the large force-generating muscles?
- Can US be used as a diagnostic tool for analysing muscle disease?
- Are muscle movement patterns related to force production?
- Does this muscle movement appear in other muscle groups?

RA patients significantly increased their hand force and hand function after exercise. However, the response to exercise from RA patients must be further evaluated. It would be

interesting to combine invasive and non-invasive methods to be able to answer the following questions:

- Would longer periods of hand exercise obliterate the differences between healthy and rheumatoid arthritis muscle force and function?
- Do the muscle's architecture, force production and decreased function depend on disease specific effects on the rheumatoid arthritis muscles?

It would be of great interest to investigate the possibility to objectively evaluate interventions, such as surgical procedures, physiotherapy and/or pharmacological treatment with the help of finger force measurements and ultrasound evaluations.

- In a longer perspective, can it be possible to establish more efficient rehabilitation programmes for RA patients through further knowledge about the muscle biomechanics?

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Human Musculoskeletal Biomechanics

Edited by Dr. Tarun Goswami

This book covers many aspects of human musculoskeletal biomechanics. As the title represents, aspects of forces, motion, kinetics, kinematics, deformation, stress, and strain are examined for a range of topics such as human muscles, skeleton, and vascular biomechanics independently or in the presence of devices. Topics range from image processing to interpret range of motion and/or diseases, to subject specific temporomandibular joint, spinal units, braces to control scoliosis, hand functions, spine anthropometric analyses along with finite element analyses. Therefore, this book will be valuable to students at introductory level to researchers at MS and PhD level searching for science of specific muscle/vascular to skeletal biomechanics. This book will be an ideal text to keep for graduate students in biomedical engineering since it is available for free, students may want to make use of this opportunity. Those that are interested to participate in the future edition of this book, on the same topic, as a contributor please feel free to contact the author.

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