HETEROGENEITY IN RESISTANCE TRAINING INDUCED MUSCLE STRENGTH AND MASS RESPONSES IN THE UPPER AND LOWER EXTREMITIES

Master’s Thesis – Faculty of Sport and Health Sciences

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ABSTRACT

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It has been reported that some muscle groups may demonstrate higher strength and hypertrophic gains in response to resistance training than others. In addition to this, the gains in strength and muscle size are highly individual. The purpose of this master's thesis is to investigate how the strength and hypertrophic adaptations compare between the elbow flexors and knee extensors in response to similar resistance training regimens. A further purpose is to study the interindividual variability in the strength and hypertrophic responses and to investigate the connection of the responses between the muscle groups.

The subjects consisted of previously untrained men and women (n = 17, 28 ± 4.9 years). The training intervention lasted seven weeks which was followed by a five-week de-training period. Resistance training was performed twice a week. The training load was individually tailored for each subject based on weekly maximum repetition tests to ensure equal loading for the knee extensors and elbow flexors. One-repetition maximum muscle strength of the elbow flexors and knee extensors was measured. Ultrasound was used to study changes in muscle architecture in m. biceps brachii (BB) and m. vastus lateralis (VL).

Maximal strength and muscle size increased significantly in both the elbow flexors and knee extensors at 3.5 weeks and further developed until the end of the seven-week training period. The total increase in VL cross sectional area (CSA) was 14.2 ± 5.9% ($p<0.05$) which was greater than in BB CSA 11.0 ± 5.7% ($p<0.05$). Larger strength gains were observed in the elbow flexors 17.0 ± 11.6% ($p<0.05$) than in the knee extensors 14.2 ± 6.5% ($p<0.05$). All variables decreased significantly in response to the five-week detraining period. Individual variability was observed in the strength and hypertrophic responses, however no correlations were observed in the responses between the upper and lower extremities.

The results suggest that the time course of muscle hypertrophy and strength adaptations are similar in the upper and lower extremities in previously untrained individuals. However, individual muscle response may vary in upper and lower body muscles.

Key words: strength training, knee extensors, elbow flexors, muscle hypertrophy, muscle strength, time-course of adaptations, individual variation

ABBREVIATIONS

BB	biceps brachii
BC	bicep curl
BMI	body mass index
CSA	cross-sectional area
EFOV	extended field of view
KE	knee extension
MRI	magnetic resonance imaging
MT	muscle thickness
PA	pennation angle
RM	repetition maximum
SWD	smallest worthwhile change
US	ultrasound
VL	vastus lateralis

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ABSTRACT

1. INTRODUCTION

The effects of resistance training on muscle health are well known and it is widely used as a training method to elicit increases in muscle hypertrophy and strength (Kraemer et al., 2002). The gains in muscle strength following systematic resistance training are due to a combination of neurological and morphological factors. Research indicates that within the first weeks of training, the increases in strength are primarily caused by neural adaptations such as increased motor unit activation of the agonist muscle groups and decreased coactivation of the antagonists. Morphological adaptations have been observed to appear in later phases of training. These include changes in the contractile characteristics of a muscle, increases in muscle volume and muscle architectural changes within the muscle. (Folland & Williams, 2007)

Resistance training has been found to increase muscle strength and size in both the upper and lower extremity musculature. The magnitude of these adaptations are relative to the demands placed on the body by the type, volume, intensity and frequency of the training. (Kraemer & Ratamess, 2004). Research suggests that some muscle groups may be more responsive to resistance training than others (Wernbom, Augustsson, & Thomee, 2007). However, there is no clear consensus as to whether the strength and hypertrophic gains are greater in the upper body compared to the lower body or vice versa. Some studies have suggested that the hypertrophic gains in the upper body may increase to a greater extent than in the lower extremities (Wernbom et al., 2007). However, no difference between the upper and lower body has been reported in strength gains. (Gentil et al. 2015).

Although it is well established that resistance training increases muscle strength and size, it should be recognized that the magnitude of these gains are highly variable between individuals (Hubal et al. 2005). The time course of strength and hypertrophic adaptations may occur more rapidly in some individuals than others (Ahtiainen et al. 2016). Identifying and understanding sensitivity to training is important and may enable the development of individually tailored training programs to effectively improve performance.

The purpose of this study is to investigate and compare the muscle strength and muscle morphological adaptations between the elbow flexors and knee extensors in response to seven weeks of similar progressive resistance training regimens in a group of previously untrained subjects. To investigate the time-course of adaptations, muscle size and strength is measured at four different time points: before, during and after the training intervention, as well as after a five-week detraining period. A further aim is to study the individual variability in the magnitude of strength and hypertrophic responses and to investigate the connection between the responses of the different muscle groups.

2. NEUROMUSCULAR ADAPTATIONS TO STRENGTH TRAINING

Systematic resistance training can lead to an improvement in athletic performance by increasing muscular strength, power and speed, muscular endurance, motor performance, developing balance and coordination as well as by increasing muscle mass (Kraemer & Ratamess, 2004). The magnitude of these adaptations is relative to the demands placed on the body. The demand can be altered through exercise type, volume, intensity, and frequency of the training (Kreamer & Ratamess, 2004). The body becomes stronger as it adapts to the increased demand and when adequate time is given for the physiological systems to recover.

The gains in muscular strength following strength training are due to a combination of neurological and morphological factors (Figure 1). Research indicates that within the first weeks of training, the increases of strength are primarily caused by neural adaptations such as increased motor unit activation of the agonists and decreased coactivation of the antagonists. Morphological adaptations have been observed to appear at later phases of training. These include of changes in the contractile characteristics of a muscle, muscle volume and muscle architectural changes within the muscle (Folland & Williams, 2007).

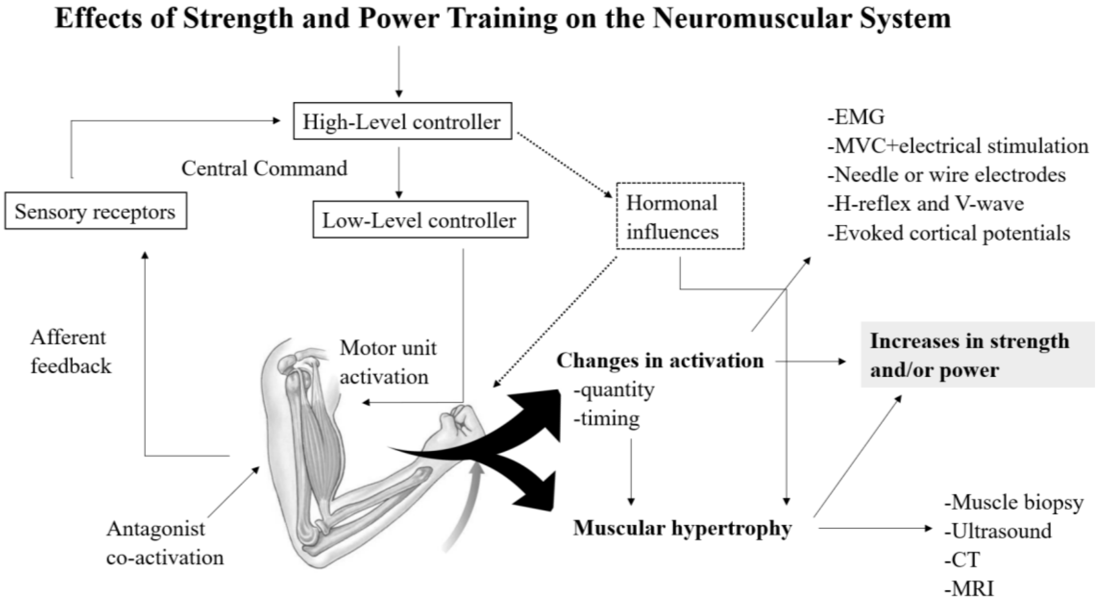

FIGURE 1. Effects of strength training on the neuromuscular system (Modified from Kraemer & Häkkinen, 2002)

2.1 Neural adaptations to strength training

It has been established that a proportion of resistance training induced strength gains are the result of changes in neural pathways and the way that these changes alter the recruitment of motor units (Aagaard et al. 2002). Evidence regarding the effects of neural factors on strength gains vary from the more suggestive, indirect evidence to more direct evidence.

When considering some the indirect evidence of neural adaptations, one indication that neural involvement plays a role in strength gains is the observed increase in muscle strength without the occurrence of noticeable muscle hypertrophy. Studies have observed that in previously untrained subjects the initial improvements in strength were accounted for neural factors and thereafter muscle hypertrophy becoming the dominant factor following the first 4-5 weeks of training (Häkkinen & Komi, 1983). Another indication that neural involvement plays a role in strength is evidenced in the ability to achieve strength gains without participating in strength training. Mental training using imagined exercise and muscle contractions has been found to increase the excitability of the cortical areas involved in movement (Guillot et al. 2009). Studies have also found that imagined training has had a positive impact on rehabilitation processes and has effectively delayed the process of muscle atrophy during periods of limb immobilization (Clark et al. 2014). Similarly, unilateral resistive exercise of one limb has been found to result in training effects in the unexercised contralateral limb. This process is referred to as cross-education and it supports the hypothesis of a central adaptation in response to training. (Gardiner, 2011). Overall, this evidence demonstrates the existence of neural plasticity and adaptation, and that the nervous system has an important role in the development of muscular strength, independent of morphological adaptations.

Although scientific literature strongly supports the idea that neural adaptation occurs due to resistance training, identifying the specific mechanism of neural adaptation that causes the improvement in force production is difficult (Walker, 2002, pp.29-32). This difficulty is caused by the interconnected system of the excitatory and inhibitory influences and by the methodological factors in previous studies (Škarabot et. al. 2020). Though much of the evidence regarding the effects of neural factors on strength is supported by more suggestive, indirect evidence, more direct evidence also exists such as changes in motor unit recruitment patterns.

Changes in motor unit recruitment patterns have been found to be associated with strength training. Synchronisation of motor unit recruitment happens at a supraspinal level and represent a reorganisation of the system. This synchronisation does not necessarily result in an increase in force but improves the coordination of the system to generate effective action potentials. This coordination also impacts synergists and has an important impact on the performance of motor skills. This change in the recruitment of motor units is an adaptation that leads to more efficient performance of tasks (Gabriel, Kamen & Frost, 2006).

Neural adaptations are essentially changes in coordination that facilitate improved recruitment of motor units and activation of the involved muscles during a specific strength task (Sale, 1988). It seems that during maximal voluntary contractions, untrained individuals are not able to activate their muscles to the full extent. Through exercise training, neural adaptations can occur that improve the agonist or synergist activation while reducing the coactivation of the antagonists muscles. (Folland & Williams, 2007) In the most part, scientific research has focused on studying the increase in agonist activation. (Walker, 2002, pp.29). It has been hypothesized that a reduction in the activation of the antagonist coactivation is linked to an increase in agonist activation and thereby force production (Carolan & Cafarelli, 1992). Agonist activation could improve through an increase in efferent motor drive, improved motor unit recruitment or firing frequency, more synchronized motor neuron firing patterns within the muscle, greater spinal motor neuron excitability and down regulation of inhibitory pathways. (Häkkinen, 1994, Aagaard & Thorstensson, 2003). Studies have attempted to directly distinguish these neural adaptation mechanisms through measurements such as surface and intramuscular electromyograph (EMG) recordings (Häkkinen & Komi 1983), nerve conduction measurements (V-wave, M-wave, H-reflex) (Aagaard et al. 2002) and through the use of transcranial magnetic stimulation (TMS) (Latella, Kidgell & Pearce, 2011).

2.2 Morphological adaptations to strength training

The process of skeletal muscle hypertrophy is complex as it is influenced by different external and internal variables. Mechanical loading is recognized as one of the main external variables and regulators that initiates the processes that cause muscle hypertrophy (Lim et al. 2022).

Human skeletal muscle is a heterogeneous tissue that is made up of functionally diverse fiber types. The variety in fiber types within a muscle allows for it to fulfil a wide range of functional requirements (Staron, 1997). Muscle fibers are categorized based on their histochemical staining features and twitch characteristics into three types; Type I (slow oxidative), Type IIa (Fast oxidative-glycolytic), and Type IIx (Fast glycolytic). Most skeletal muscles consist of a combination of all three types of skeletal muscle fibers. The proportions of the type of muscle fibers however may vary depending on the muscle in question and the action of the muscle, the training background of the individual as well as genetic factors (Ahmetov, Vinogradova & Williams, 2012).

Research has created a clear understanding of the macroscopic and microscopic changes that occur in the muscle when the mechanical environment is changed. (Wisdom et al. 2014) According to the ´Hennemans size principle´, during low level muscle contractions, only the smaller low-threshold motor units are primarily recruited. Conversely, when more force is required, there is an additional progressive recruitment of larger high-threshold motor units (Aagaard & Thorstensson, 2003). When the intensity of resistance training is high, both low and high threshold motor units activate, involving both type I and type II muscle fibers. Consequently, exercise can induce significant alterations in muscle fiber morphology. Muscle fibers can adapt to changing demands by changing fiber type composition or size of the muscle fibers (Jorgenson et al. 2020). Resistance training has been linked to alterations in muscle fiber subtype (Häkkinen et al. 1998, Campos et al. 2002). The ability to enhance the muscles contractile activity and energy availability during exercise is dependent on this ability to interchange skeletal muscle fibers from a more glycolytic fiber to a more oxidative fiber (Yan et al. 2011).

Mechanical tension, metabolic stress and muscle damage have all been suggested as possible mechanisms for developing muscle hypertrophy (Schoenfeld, 2010). Muscle fiber hypertrophy induced by resistance training refers to the increase in the protein content and in size of the existing muscle fibers and it is often associated with an increase in the CSA or total volume of the trained muscle. Exercise induced hypertrophy has been found to mostly result from an increase of sarcomeres and myofibrils in parallel (Jorgenson et al. 2020). When a skeletal muscle is overloaded, the stimulus causes damage to the muscle tissue. This begins a series of myogenic events that eventually increase the size and the amount of myofibrillar proteins, actin and myosin, while increasing the total number of sarcomeres. This is followed by an increase in the diameter of individual myofibers, resulting in a larger cross-sectional area (CSA) of the whole muscle (Schoenfeld, 2010). More recent studies have also suggested that myofibers undergo longitudinal growth (Jorgenson et al. 2020). These different mechanisms of mechanical load-induced skeletal muscle hypertrophy at the microscopic level are illustrated in Figure 2.

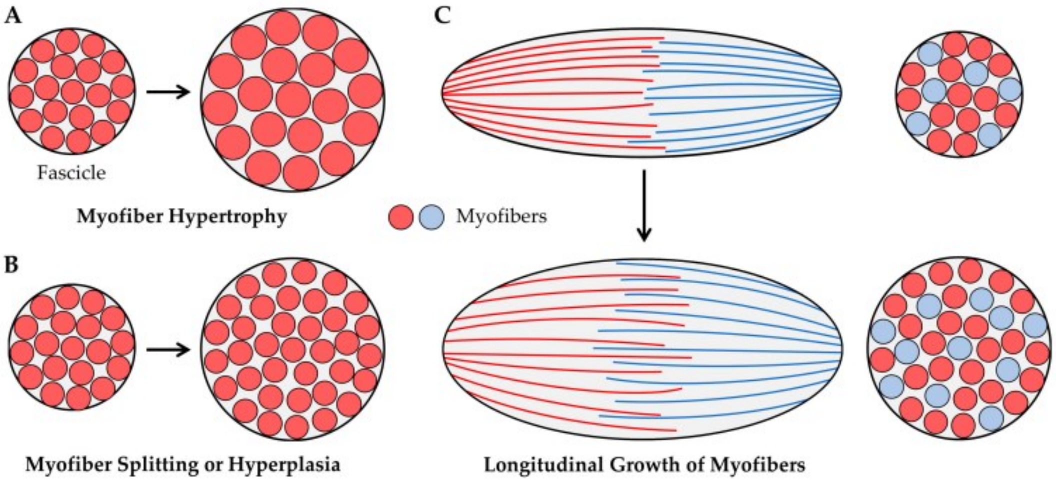

FIGURE 2. Illustration of muscle growth through a) myofiber hypertrophy b) myofiber hyperplasia c) longitudinal growth of myofibers (Jorgenson et al. 2020)

Muscle hyperplasia and myofiber splitting (Figure 2) can be considered distinct from muscle hypertrophy as it refers to muscle growth due to the generation of new muscle fibers. The main challenge in evaluating hyperplasia in humans is the difficulty in quantifying the amount of individual muscle fibers. Animal studies to support mechanical overload induced muscle hyperplasia exist (Kelley, 1996), however evidence to support this mechanism in humans is limited (Gardiner, 2011).

In order for the muscle to grow, new contractile proteins are required. In the process of muscle protein synthesis outpacing muscle protein breakdown, new contractile proteins are generated (Schoenfeld, 2010.). Satellite cells play an important role in this process of cellular hypertrophy and muscle growth (Folland & Williams, 2007). Satellite cells are located under the muscle cell basal membrane and activate when sufficient mechanical stimulus is applied to a muscle (Jorgenson et al. 2020). In other words, satellite cells play a role and activate when lesions in the muscle require muscle regeneration. Once activated, satellite cells create new myonuclei to the muscle cell though proliferating, differentiating and fusing to existing myofibers. The satellite cell derived myonuclei produce muscle specific proteins that contribute to the increase in myofiber size and support muscle growth (Favier, Benoit & Freyssenet, 2008).

Studies have found that resistance training increases muscle fiber hypertrophy in all fiber types (Häkkinen et al., 2003, Vissing et al., 2008, Ruple et al., 2021). A greater relative hypertrophy has been found to occur in the type II muscle fibers. A study by Campos et al. (2002) found that in a group of previously untrained men, after eight weeks of progressive resistance training, all three major fiber types increased size in the low repetition (<5 (repetition maximum) RM) and intermediate repetition (9-11RM) training groups. The CSAs of the major fiber types increased by approximately 12.5% for type I, 19.5% for type IIA, and 26% for type IIB. Similarly, Aagaard et. al (2001) found that average fiber CSA increased 16% after 14 weeks of heavy resistance strength training, however when separated into fiber types, type I fiber area did not reach statistical significance, while type II fiber area increased 18%. When considering the time course of adaptations these findings suggest a more rapid hypertrophy response for type II fibers in response to heavy resistance strength training.

2.2.1 Muscle cross-sectional area

It is well established that strength has a relationship with skeletal muscle mass (Morris, 1948). A major morphological adaptation that is specific to resistance training is an increase in the CSA of the trained muscles. To be able to accurately measure changes in muscle CSA is therefore a useful method for a researcher or practitioner to assess the effectiveness of an intervention such as a resistance training program.

The anatomical CSA (ACSA) and physiological CSA (PSCA) differ from one another based on the perspective in which the CSA of the muscle is being assessed. The ACSA of a muscle is measured perpendicular to the longitudinal axis of the muscle and does not consider the direction of the muscle fibers. ACSA does not therefore accurately represent the number of muscle fibers in a muscle. PCSA is the sum of the CSA of all fascicles within the muscle and is directly influenced by the pennation angle (Timmins et al. 2016). Figure 3 illustrates the difference between the ACSA and PCSA as well as other characteristics of muscle architecture such as fascicle length and fascicle pennation angle (PA).

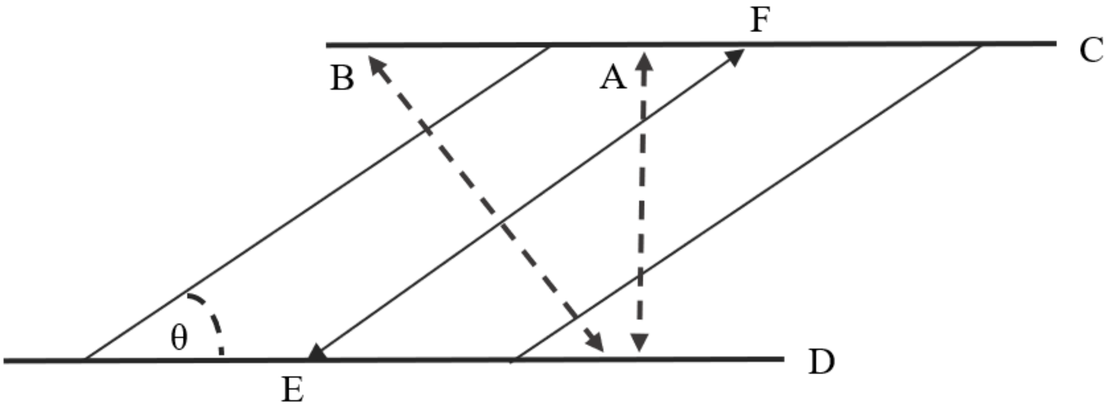

FIGURE 3. Characteristics of muscle architecture. A: anatomical cross-sectional area (ACSA), B: physiological cross-sectional area (PCSA), θ: pennation angle (PA), C: superficial aponeuroses, D: intermediate aponeuroses, E-F (distance between aponeuroses): fascicle length (Modified from Timmins et al. 2016).

On the whole muscle level, depending on the type, the duration and design of the resistance training program, studies have observed that progressive resistance training typically induces a 5–20% increase in the trained muscle size within 8–16 weeks (Jorgenson et al. 2020). In a recent study by Sterczala et al. (2019), 16 previously untrained men completed eight weeks of resistance training on the lower limbs, while eight men served as controls. Vastus lateralis (VL) muscle CSA was analyzed using extended field of view (EFOV) ultrasound (US) imaging. Following the resistance training period VLCSA increased significantly (~ 18.7%) in the resistance training group while a non-significant increase in CSA was observed in the control group. Vissing et al. (2008) reported an increase in quadriceps CSA by ~10% following 12 weeks of progressive resistance training. Similarly, Aagaard et al. (2001) observed a 10-12% increase in quadriceps CSA following 14 weeks of heavy resistance strength training of the lower limb muscles.

2.2.2. Muscle architecture

Skeletal muscle fibers within a muscle are arranged in bundles also referred to as fascicles. Within the muscle fascicle, the muscle fibers are parallel to one another. Fascicle arrangements refer to the arrangement in which the fascicles are positioned in respect to the tendons. Fascicle arrangements vary between muscles, resulting in muscles with different shapes and functional capabilities. The contraction properties, distribution of muscle fibers in a muscle, and muscle arrangement around a joint all influence the force-length and force-velocity relationship of a muscle (Tortora & Derrickson, 2014).

The architectural characteristics of a muscle include muscle CSA and several other characteristics. These include muscle thickness, which refers to the distance between the superficial and deep aponeuroses of a muscle, fiber PA, which refers to the orientation of the muscle fascicles within a muscle, and fascicle length which represents the length of the muscle fascicles running between the aponeuroses of a muscle (Figure 3) (Timmins et al. 2016).

The orientation of the muscle fascicles can be determined by assessing the angle of fiber pennation using US imaging. Resistance training has been observed to increase muscle pennation angle as well as muscle thickness and larger pennation angles have been linked to the muscles capacity to produce high forces. (Aagaard et al. 2001) The mechanisms that have been found to contribute to high force production in pennated muscles have to do with the increased PCSA. The increase in PCSA allows for the muscle fibers to function at more optimal lengths (Blazevich 2006). In the study by Aagaard et al. (2001) eleven male subjects undertook 14 weeks of resistance training of the lower limbs. Muscle architectural characteristics were assessed including muscle thickness and fiber pennation angle in the VL muscle. Following the training period an increase in muscle thickness was observed as well as an increase in VL fiber pennation angle from 8.0º to 10.7º. Other studies have found even more significant increases in fiber pennation angle following only five weeks of heavy resistance training (Blazevich et al., 2007). Interestingly, studies using different training protocols such as plyometric training have found similar increases in muscle thickness however a decrease, as opposed to an increase, in fiber pennation angle (Blazevich et al. 2003). These findings represent that muscle adapts differently to different types of stimuli. Furthermore, these changes in muscle architecture support the theory of improved shortening velocity of muscle fascicles and increase in force production (Walker, 2002, pp. 34).

2.2.3 Measuring skeletal muscle morphology

Previous studies have analyzed muscle morphological adaptations in relation to resistance training using different methods. Studies have obtained measures of muscle morphology at the microscopic scale using biopsy samples to determine changes in single muscle fiber CSA (Häkkinen et al. 2003, Mero et al. 2012). On a macroscopic scale, total anatomical muscle volume and muscle CSA have been measured with the use of different imaging techniques such as magnetic resonance imaging (MRI), (Aagaard et al. 2001, Ahtiainen et al. 2003), ultrasound (US) (Sterczala et al. 2019) and computed tomography (CT scans) (Suetta et al. 2004).

MRI is considered the most accurate method in determining the CSA and volume of individual muscles and muscle groups because of the high resolution of the images and the ability to assess muscle size at different locations along the muscle length (Pons et al. 2018). Due to the limited availability of MRI, US is a less expensive alternative that is both valid and reliable for assessing large individual human muscles. (Noorkoiv et al. 2010) US images provide high resolution images of superficial soft tissue anatomy and structures. Standard US does not have many contraindications for it being a non-invasive imaging procedure. When comparing to

MRI, the US images are created based on physical changes in composition as to with MRI, images are provided based on the chemical changes in the structures (Baloch et al. 2018). The images produced by US are unique due to the ability to define anatomy of structures depending on their echo qualities. Skeletal muscle is comprised of contractile proteins as well as non-contractile elements. These include intramuscular adipose tissue and fibrous tissue. When examining muscle tissue with brightness mode (B-mode) US imaging, these different elements and structures provide varying levels of pixel intensity which is also referred to echogenicity. In practice this means that skeletal muscle appears as hypoechogenic which refers to dark or black tones and both fibrous and intramuscular adipose tissue appears as hyperechogenic which refers to light and white tones (Stock and Thompson, 2020). Bones and blood vessels are anechoic which means that they appear in black in the images.

US has been widely applied in medical field as a diagnostic tool as well as in the field of sports science as a tool in musculoskeletal interventional procedures and research as it allows for repeatability which is helpful in monitoring response to treatment or intervention (Baloch et al. 2018). Conventional B-mode US can be used for both transverse and sagittal scans of skeletal muscle to examine skeletal muscle characteristics and architecture such as fascicle pennation angle, fascicle length, adipose tissue, muscle size and quality (Franchi et al. 2018). Transverse scans allow images of anatomic CSA of muscles or muscle groups to be obtained, sagittal scans allow assessment of muscle architecture.

Extended field of view (EFOV) US imaging technique is used to study longer anatomic structures. This technique relies on texture mapping algorithms and puts together a series of images to reconstruct one large panoramic image (Franchi et al. 2018). When used in transverse plane, EFOV is a valid (Ahtiainen et al. 2010) and reliable (Noorkoiv et al. 2010) method to detect training induced changes in CSA of larger skeletal muscles. EFOV represents a reliable alternative to MRI in the assessment of lower and upper extremity muscle CSA although the images tend to systematically produce slightly smaller estimates of muscle CSA compared to the values obtained from MRI (Ahtiainen et al., 2010, Chan, Newton & Nosaka, 2012).

Despite the several advantages of B-mode US, there are certain limitations that cause challenges. Some of these limitations include of the user dependency as well as long training periods (Franchi et al. 2018). The relatively small field of view and limited penetration of US into deeper structures can lead to the difficulty in assessing deeper tissues, obese patients and areas deep to bone. (Baloch et al. 2018). Also, when assessing the CSA of a skeletal muscle, it is important to considered that the CSA includes of all the various parts that make up the total muscle CSA. These include also the non-contractile elements and tissue such as blood vessels. Changes in intravascular length, mitochondrial density, and muscle glycogen density are all common adaptations related to resistance training that also may contribute to muscle CSA and should therefore be noted (Jones et al. 2008).

When assessing changes in muscle morphology it is important to note that changes in muscle architecture take place in a non-homogeneous manner and that hypertrophy differs along the muscle length (Wells et al. 2014). Studies have found that specific regions of the muscle may be more responsive to muscle growth than others. Although increases in muscle CSA have been observed in all regions of the muscle following training, the earliest and most significant increases in hypertrophy have been detected in the distal (Vikne et al. 2006) and proximal regions of the muscle (Ahtiainen et al. 2003, Monti et al. 2020).

2.3 Time course of adaptations

Strength training studies typically involve training interventions that last 8-12weeks. In these studies, the early increases in strength have been associated mainly with neural adaptations such as improved coordination, learning and increased activation of prime mover muscles (Sale, 1988). Although the overall effects of training have been described in numerous previous studies, the detailed timeline of the adaptations has not fully been established due to the too large unmonitored phases in between measurement points during the intervention (Brown et al. 2017). Muscle hypertrophy has been often stated to be minimal during the initial stages of resistance training, however contrary to this hypothesis, several recent studies have observed that the hypertrophy process begins earlier and that previously untrained subjects have achieved considerable and rapid increases in both muscle size and strength following just 3-4 weeks of resistance training (Stock et al., 2016, Jenkins et al., 2016). The hypertrophy observed within the first few weeks of resistance training in previously untrained individuals could in part be a result of muscle adema due to unaccustomed exercise (Damas et al. 2015).

2.3.1 Muscular adaptations following detraining

Detraining refers to the period when subjects do not take part in any form of training. As skeletal muscle is known for its adaptability and by its ability to adjust to a wide range of functional demands. In situations when the training stimulus is insufficient, muscular detraining occurs (Mujika & Padilla, 2000). Detraining in the long run causes decreases in muscle force. This decrease in muscle force caused by inactivity can be explained by the neural and muscular adaptations that take place (Häkkinen et al. 2000).

The effects of detraining on skeletal muscles appear to be dependent on the duration of the inactivity period (Mujika & Padilla, 2001). Relatively short-term detraining periods of 3-4 weeks have been studied to result in non or minimal changes in maximal strength and hypertrophy in the lower extremities in previously untrained subjects (Häkkinen et al. 2000, Räntilä et. al.,2021). Prolonged detraining of 12-24 weeks have been found to cause muscle atrophy, decrease mean muscle fiber areas of both fiber types as well as cause significant decreases in maximal strength and maximal iEMG of the leg extensors (Häkkinen, Alen & Komi, 1985., Häkkinen et al. 2000, Mujika & Padilla, 2001)

It is important to note that de-training may impact individuals differently depending on the degree of the responses. A recent study investigating differences in individual responses by Räntilä et. al (2021) observed that subjects that showed high responses in hypertrophic gains following 10 weeks of strength training, also demonstrated a larger decrease in muscle mass and strength during a six-week de-training period compared to other subgroups. These findings suggest that not only do strength gains and muscle activation adaptations occur at different times depending on the individual, but that de-training effects may also vary.

Most of the data regarding de-training has been gathered through studies focusing on the lower extremities. Not much data available on the effect of de-training on the muscles of the upper extremities. A study by Shaver (1975) however, studied the effects of different durations of inactivity periods (1, 4, 6, and 8 weeks) on the maintenance of recently acquired levels of muscular strength in the ipsilateral and contralateral arms following six weeks of unilateral training of the upper limbs. The results indicated that there was no significant loss of the newly acquired isometric strength gains following one week of de-training. Significant losses were however observed at four weeks and decreased progressively until eight weeks of the entire de-training. Strength however remained elevated above preconditioning levels throughout the entire de-training period.

2.3.2 Influence of muscle group

It has been recognized that some muscles are more, and some are less responsive to the stimulus of strength training (Wernbom et al. 2007). Strength training studies have observed a greater hypertrophic response to resistance training in the upper extremities compared to lower extremities even though the relative intensity and volume of the training has been similar (Folland & Williams, 2007). Abe et al. (2000) investigated the time course of skeletal muscle adaptations in the upper and lower body following 12 weeks of progressive heavy resistance training in untrained men and women. Muscle thickness and dynamic strength was assessed throughout the 12-week training period. The results showed a gradual increase in muscle thickness in all muscle groups in both sexes (Figure 4). Men demonstrated a muscle thickness percentage increase of 12-21% for the upper body and 7-9% for the lower body musculature. Women demonstrated slightly higher muscle thickness percentage increases of 10-31% for the upper body and similar 7-8% increase for the lower body musculature. Based on their findings the study concluded that significant increases in muscle thickness can occur after six weeks of resistance training, however the upper body responds faster and in greater magnitude compared to the lower body. A possible explanation for this difference in hypertrophic gains between the upper vs. lower extremities is that the leg muscles are routinely activated and loaded to a larger extent during activities of daily living than the upper body musculature which may reduce the potential for further muscular responses induced by the exercise overload stimulus. (Folland & Williams, 2007).

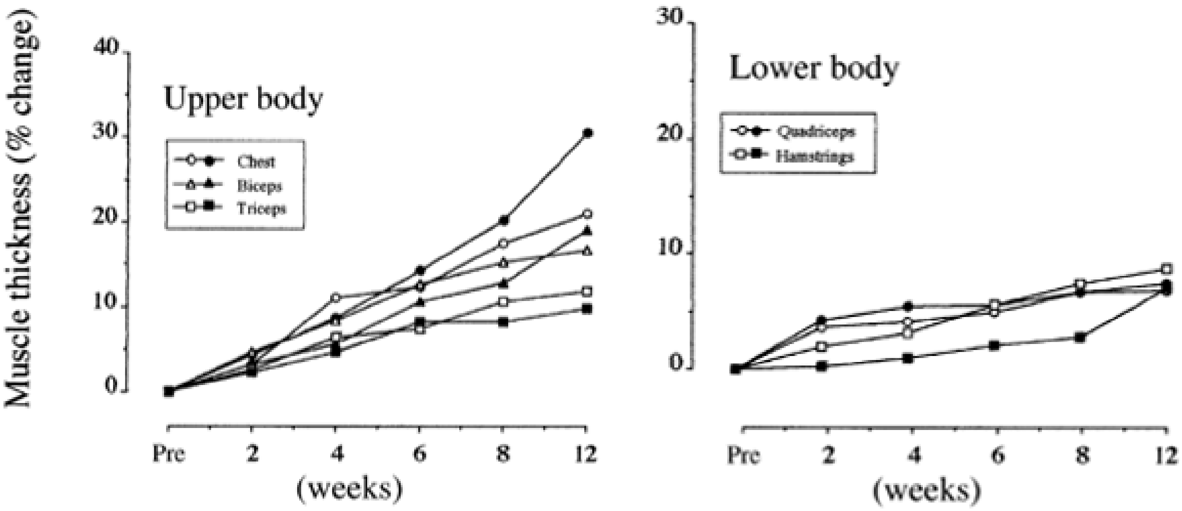

FIGURE 4. Relative percentage increases in skeletal muscle thickness over 12 weeks of resistance training in men (unfilled symbols) and women (filled symbols). (Abe et al. 2000)

When it comes to the changes in maximal strength, the lower and upper body strength have been found to increase progressively throughout training (Abe et al. 2000). There is no clear consensus about the theory that the upper body strength would respond to a greater degree than the lower body or vice versa (Gentil et al. 2015). A recent review by Thompson et al. (2020) observed that strength training studies have reported greater relative improvements in maximal strength in the lower body exercises than in the upper body exercises. The authors suggested that this could be due to the recruitment of larger muscle groups and the exposure to higher loads. A challenge in the interpretation and comparison of the results of previous resistance training studies is the difference in the strength training protocols applied for the different muscle groups.

A study by Gentil et al. (2015) compared the strength gains between the elbow flexors and knee extensors in response to similar training regimens. The subjects included of 55 previously untrained women. The training intervention lasted for a total of 10 weeks that included of two training sessions a week. Unilateral knee extension and elbow flexor peak torque was measured before and after the training. The results indicated significant increase in strength in both the elbow flexors (11.74%) and the knee extensors (11.45%) and showed that the muscles in the lower and upper extremities presented similar strength gains following resistance training. Individual variability was observed in the magnitude of the responses, however there was no correlation between strength gains between the upper and lower body indicating that individual muscle response may vary between different muscle groups.

3. INDIVIDUAL RESPONSIVENESS TO STRENGTH TRAINING

As previously discussed, resistance training has been found to increase muscle size and strength in both men and women. Although studies support this phenomenon, the individual variability in the strength and gains in muscle size following resistance training should be recognized. While positive relationships between muscle force production and muscle CSA have been shown (Jones et al. 2008), some studies examining relationship between force and muscle CSA have reported inconsistent findings. Some training studies have revealed that individuals have shown either improvements in muscle hypertrophy with non-significant changes in strength and some have revealed increases in strength with minimal or statistically insignificant changes in muscle hypertrophy following resistance training (Sale et al. 1992, Ahtiainen et al. 2016).

This reflects to the fact that people are unique and may react differently to different types of physical stimuli. When considering the time course of adaptations, some may experience strength or hypertrophic gains more rapidly than others. There are many factors that have been discussed that may play a role in the differences between individuals in the responsiveness to resistance training. These factors include of the subjects age, sex, training background and nutrition as well as hormonal, neural and metabolic factors (Schenes & Kraemer, 2002). Gender is usually considered the most significant factor as muscle mass and higher levels of anabolic hormones affect the response level (Ivey et al. 2000). Studies however indicate that the magnitude of strength and hypertrophy gains following resistance training are not dependent on gender. A study by Ahtiainen et al. (2016) observed that gender did not influence training induced responses in muscle size and strength and that both women and men demonstrated equal diversity in the responses regardless of age. The study by Hubal et al. (2005) assessed sex differences in strength and muscle size gains following resistance training of the upper limbs. Men demonstrated a small advantage (2.5%) in relative muscle size gains over women. However, women reported a more significant relative increase in dynamic strength than men (64% vs 40%). Similarly, Cureton et al. (1988) has reported a more significant increases in upper body dynamic strength for women than men (~36% vs ~59%).

3.1 Variability in strength and hypertrophic adaptions

The study by Hubal et al. (2005) investigated the variability in the strength and muscle size gains in a total of 585 subjects including both women and men following a 12-week resistance training program designed to progressively train the elbow flexors. One-repetition maximum (1RM) of the elbow flexor muscles and CSA of the biceps brachii were assessed before and after the training intervention. The subjects demonstrated a large range of hypertrophic responses to training as 6% of the subjects showed practically no gains in muscle CSA, ~40% showed 15-25% increase in muscle CSA, while ~2% showed >40% gains in muscle CSA. Similarly, the subjects demonstrated a large variability in muscle strength gains with ~40% of the subjects showing an increase of 40-60% in their 1RM, ~6% increasing their 1RM by >100% and 2% gaining less than 5%. Ogasawara et al. (2016) studied the changes in muscle CSA of biceps brachii, quadriceps femoris and hamstrings musculature following a 12-week resistance training program. The results indicated individual variability in muscle hypertrophy in all the studied muscle groups. Other resistance training studies have also reported that muscle size gains (Phillips et al. 2013) as well as strength gains are highly individual (Erskine et al. 2010).

Resistance training studies have begun to identify and quantify the proportion of subjects into low and high responders for gains in strength and muscle size. Identifying different types of responders is necessary in recognizing the different mechanisms controlling muscle growth. When understanding the mechanisms behind individual responsiveness to resistance training, training programs can be tailored to optimize training outcomes (Roberts et al. 2018).
Studies have generated cohorts and defined high and low responders to resistance training in different ways depending on the methods used in the studies. For example, some studies have used muscle imaging techniques to measure pre and post resistance training changes in muscle thickness (Mobley et al. 2018), muscle CSA (Ahtiainen et al. 2016) and whole muscle size (Ogasawara et al. 2016). Some studies have used the pre and post changes in fiber CSA (Bamman et al., 2007) and some changes in whole-body lean tissue mass (Davidsen et al. 2011).

Ahtiainen et al. (2016) studied the heterogeneity of responses in previously untrained men and women that had taken part in a 20-24week lower body resistance training program. Approximately seven % of the subjects were considered as low responders for their gains in strength and muscle size. Some on the other hand demonstrated remarkably high training responses. The majority of the subjects however were neither high or low responders in both muscle size and strength (Figure 5).

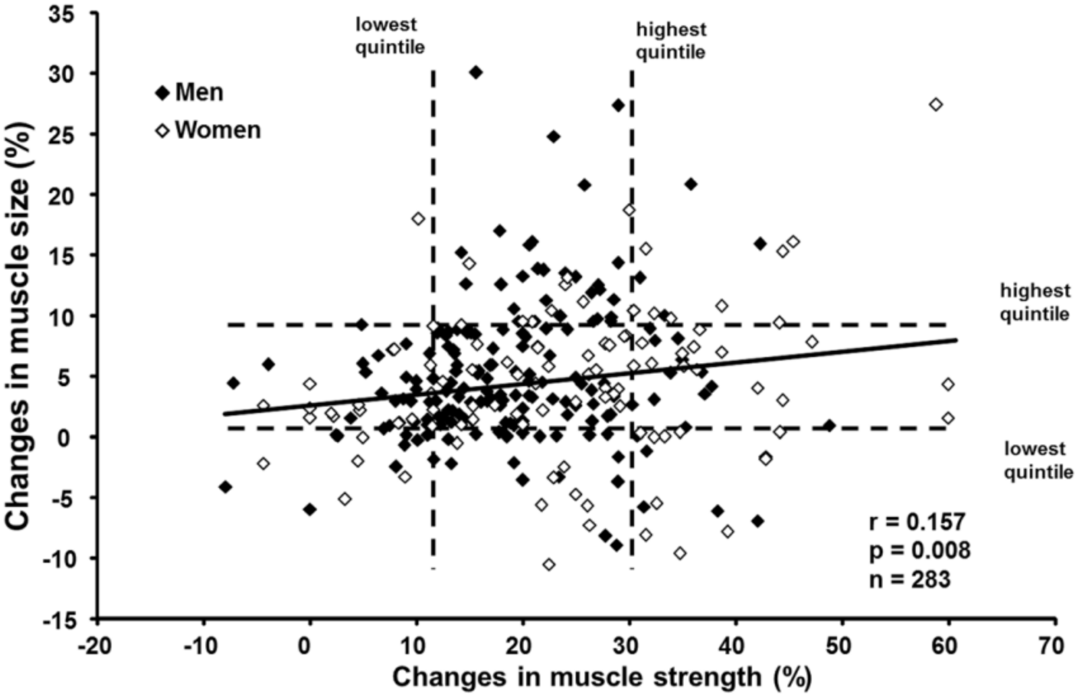

FIGURE 5. Relative changes in strength and muscle size following training. The highest and lowest quintiles in changes in muscle size and strength are represented as the dashed lines (Ahtiainen et al. 2016).

Low responders typically tend to experience little or no gain in muscle size or strength. For the resistance training induced changes in muscle size and strength Ahtiainen et al. (2016) used a non-training control group in the determination of low responders. Subjects were considered as low responders (LR) if their training response was below the upper 95 % CI of the control group. Subjects were considered as high responders (HR) if their training response exceeded one SD from the mean of the training group. Räntilä et al. (2021) did not utilize a control group in the determination of LR, however separated the subjects based on the percentual increases in vastus lateralis CSA into LR (<4.5%), medium responders (MR) (4.5-15%) and HR (>15%). Regarding changes in muscle thickness the study by Mobley et al., (2018) measured VL MT before and after 12 weeks of resistance training and categorized the responses using cluster analysis. The VL MT responses were used to differentiate low, medium and high responses as follows: (means ± SD, (range): LR = 0.11 ± 0.14 cm (-0.28 to 0.25 cm), MR= 0.40 ± 0.06 cm (0.29 to 0.52 cm) and HR 0.69 ± 0.14 cm (0.59 to 1.20 cm). Franchi et al. (2018) has however pointed out that even small increases in muscle thickness may reflect considerable increases in total muscle volume. This should be considered when categorizing responses based on changes in muscle thickness alone.

3.2 Classifying individual responses

Whenever a measurement is obtained it is important to consider that the measurement can be influenced by measurement error. Causes contributing to measurement error and affecting an individuals observed response can be a result of one or a combination of random variation and within-subject variation (Hopkins, 2015). Sources of random variation can relate to experimenter reliability, technical errors related to the equipment used in the data collection as well as the day-to-day variability in performance due to biological factors. Within-subject variation can be resulted by changes in the environment or changes in behavior. Changes in sleep patterns, mental or physical fatigue and diet can influence the mental and physical state of an individual. These are all factors capable of modifying the measured variable and contributing to measurement error. Within-subject variation has been found to be related to the intervention duration, with longer intervention periods believed to enhance the potential influence (Hrubeniuk et al.2021). To reduce measurement error and increase the accuracy of an individual's true value, repeating the measurements on different occasions and taking the mean of repeated measurements during a single time point is recommended (Hopkins, 2004). Technical error and day to day biological variability has minimal influence on detecting patterns in group responses following training interventions. However, on an individual level they can impact the true observed change in performance over time (Heckstteden et al. 2015).

Study designs including a control group are recommended when it comes to categorization of individual responses. The variance in the scores of the participants that do not take part in the intervention can be interpreted as the product of within-subject and random variation (Hopkins, 2015). Standard deviation of individual responses (SDIR) can be calculated using the following equation: Variance of the intervention group change scores – variance of the control group change scores. SDIR is thereby used to estimate the impact of individual responses to the intervention on overall heterogeneity, taking into consideration the impact of the different sources of variation and measurement error (Hrubeniuk et al., 2021). Hopkins (2015) states that to compensate for a large error of measurement, quantification of individual responses requires a large sample size or averaging repeated measurements.

Categorizing individuals as responders or non-responders to an intervention refers to the ability for a participant to progress beyond a certain threshold value for a particular variable or outcome. A fundamental criterion for determining a responder is that the individual improves significantly, which requires that the individual change is greater than estimated measurement error (Hays & Peipert, 2021). Hrubeniuk et al. (2021) highlight that participants should be grouped into responders and non-responders only when the study design includes of a separate control group and the data of the control group is utilized in the categorization process. The authors argue that when a control group is absent, the individuals can be categorized as only either experiencing a benefit or not experiencing a benefit from the intervention.

There are different types of response thresholds that have been used in previous studies. Hrubeniuk et al. (2021) list that the most common approaches of setting these include of using the upper limit of observed differences expected as a result of variation, zero change as a constant value and the lower limit of clinically meaningful difference. Lower limit of clinically meaningful difference or practical relevance refers to a response threshold that separates an insignificant and a meaningful response from one another. When choosing a threshold to set the lower limit of practical relevance, the authors recommend to use the smallest worthwhile change (SWC) (0,2 x SD of baseline values) as it is considered to be a method that can accurately determine a meaningful change. Tests that have good test-retest reliability are favorable when calculating the SWC as they produce the lowest variation between tests. Although using the SWC is an acceptable alternative in setting the lower limit of practical relevance when a control group is lacking, the calculated value is specific to the sample and restrict generalizability. (Hrubeniuk et al., 2021).

4. PURPOSE OF THE STUDY, RESEARCH QUESTIONS AND HYPOTHESES

The purpose of the study is to investigate and compare the muscle strength and muscle morphological adaptations in the elbow flexors and knee extensors and to explore the individual variability in the responses. Furthermore, the purpose is to examine whether the individual strength and hypertrophy response varies in the upper and lower body muscles.

Research questions:

RQ1: Does seven weeks of resistance training lead to significant changes in muscle CSA and architecture in the upper and lower extremities?

H1: Yes. Previous studies utilizing similar duration training interventions have reported significant increases in muscle size in the lower extremities (Sterczala et al. 2020, Seynnes et al. 2007) and in the upper extremities (Pedrosa et al. 2023). Significant changes in MT have been observed in the upper (Jenkins et al., 2016, Abe et al. 2000) and lower extremities (Tillin et al. 2012). Also, fiber PA has been observed to change in response to resistance training in the lower extremities (Blazevich et al. 2007).

RQ2: Does seven weeks of resistance training lead to significant changes in maximal muscle strength in the upper and lower extremities?

H2: Yes. Significant increases in muscle strength have been observed in the early weeks of resistance training in the upper (Abe et al. 2000) and lower extremities (Ahtiainen et al. 2003)

RQ3: Do the upper and lower extremities respond similarly to seven weeks of progressive resistance training?

H3: No.
Hypertrophic adaptations: Strength training studies have observed a greater and more rapid hypertrophic response to resistance training in the upper extremities compared to lower

extremities even though the relative intensity and volume of the training has been similar (Abe et al. 2000, Wernbom et al. 2007). A possible explanation for this difference in hypertrophic gains in the upper extremities, compared to the lower extremities is that the leg muscles are habitually activated and loaded to a larger extent during activities of daily living than the upper body musculature which may reduce the potential for further muscular responses induced by the exercise overload stimulus. (Folland & Williams, 2007).

Strength adaptations: Strength training studies have reported greater relative improvements in maximal strength in the lower body exercises than in the upper body exercises. This could be due to the recruitment of larger muscle groups of the lower limbs and exposure to higher loads (Thompson et al. 2020).

RQ4: Is there individual variability in the strength and hypertrophic responses of untrained subjects in response to seven weeks of progressive resistance training?

H4: Yes.

Individual variability in the strength and hypertrophic responses have been observed in previous strength training studies in both upper and lower extremities. (Hubal et al. 2004, Ahtiainen et al. 2016)

5. METHODS

5.1 Subjects

The subjects consisted of 17 previously untrained (28 ± 5 years) men (n= 10) and women (n= 7). The physical characteristics of the subjects are presented in Table 1.

The exclusion criteria for the participants included: (1) those who were not in the age range of 18-35 years, (2) those who practiced resistance training regularly within the past six months, (3) those with backgrounds in systematic endurance-type training, (4) those with history of medication that could affect exercise responses or that are currently consuming any anti-inflammatory drugs, (5) those with any acute or chronic illness affecting cardiovascular, respiratory, musculoskeletal and/or endocrine function or any other condition that may limit their ability to perform resistance training and testing, and (6) those that smoke. Pre-participation health screening was conducted for each subject. The subjects were required to attend at least 12 out of 13 of the training sessions to be included in the study. The subjects were instructed not to take part in any other resistance training during the resistance training and de-training periods.

The subjects were recruited through local advertisements published around the Jyväskylä University campus, social media and e-mail lists. The subjects were carefully informed about the design of the study. Signed written informed consent to participate in the study was collected from all subjects. The study was approved by the Ethical Committee at the University of Jyväskylä and the measurements were completed in accordance with the declaration of Helsinki.

TABLE 1: Physical characteristics of the subjects

N	Sex	Age (years)	Height (cm)	Weight (kg)	BMI	SMM	Bodyfat (%)
17	7 women 10 men	28 ± 5	176 ± 10	83 ± 21	26 ±5	33 ± 8	28 ± 7

5.2 Study Design

The total duration of the study was 14 weeks of which the first two weeks acted as a control period. During the control period the subjects were instructed to maintain their normal recreational activities and no resistance training was to be carried out. Muscle size and maximal strength of the subjects was tested five time points: two weeks before the control period (control-tests), at baseline (pre-tests), after 3,5 weeks (mid-tests) and after seven weeks of progressive strength training (post-tests), and finally after five weeks of de-training (de-training post-tests) (Figure 6). Furthermore, anthropometry measurements were collected from the subjects throughout the study period.

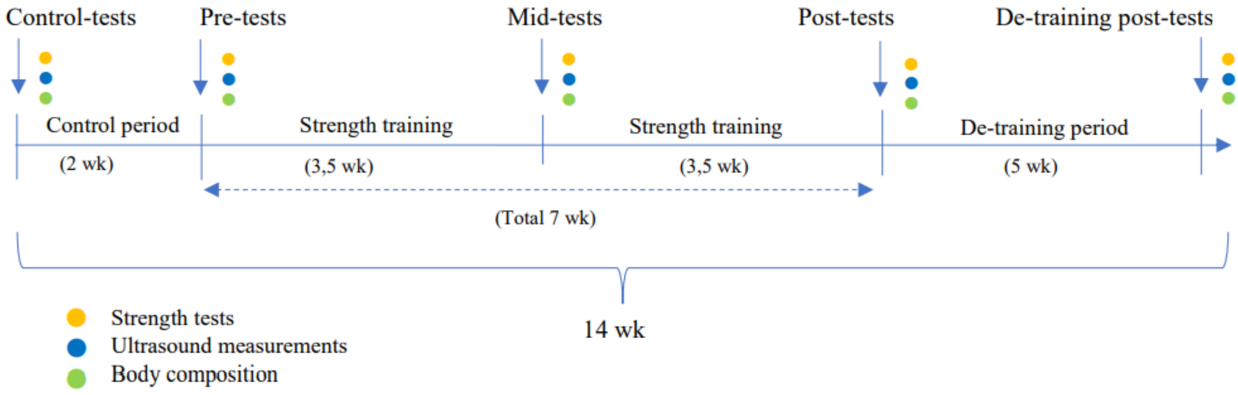

FIGURE 6. Study design indicating the five measurement points during the 14-week intervention period.

The de-training period was five weeks and it began after the post-training measurements. During the de-training period the subjects were instructed to not take part in any resistance, body weight or high intensity aerobic training nor to increase the amount of aerobic training from their routine amount. The subjects were instructed to continue their normal lifestyle and recreational activities as usual and not make any changes to their normal activity levels.

5.3 Strength training

The subjects participated in supervised strength training (total of 13 sessions) twice a week for a total of seven weeks. A minimum of 48 hours of rest was required between the training sessions each week to allow for full recovery. Assistant researchers supervised all the training sessions.

The training session began with a warm-up that consisted of five minutes cycling at a self-determined pace followed by dynamic movements with bodyweight. These included of squat, lunge, moving from standing to push-up position and back to standing, alternating knee hug with calf raise and side squats. Following the bodyweight movements, five maximal counter movement jumps were performed (CMJ).

After performing the warm-up, the following exercises were performed in each training session: two exercises for the lower extremities, bilateral knee extension exercise and the bilateral leg press. Three exercises for the upper extremities: barbell bicep curl, bilateral bench press and chest supported T-bar row. The concentric phase of the exercises was performed rapidly, and the eccentric phase was controlled to two seconds.

To maximize strength and hypertrophy gains, the subjects need a suitable amount of exposure to high intensity repetitions, which are adjusted based on their one repetition maximum (1RM) for that given exercise, as well as adequate total training volume per week (number of repetitions per week) (Morton et al., 2019, Thompson et al., 2020). Therefore, strength training took place with progressive training loads of 60-80 % of the 1RM strength measured or estimated at the baseline. The number of the sets for each exercise was set at 3-5 depending on the exercise (three sets of leg press, bench press, T-bar row. Five sets of knee extension and bicep curl). The number of repetitions were set at 8-10 per set. Since skeletal muscle hypertrophy relies on high levels of effort regardless of load (Morton et al., 2019), during the second training of the week, the last set of each exercise was performed to concentric failure. The repetitions in the last set of each exercise (from second training of the week) were used to adjust the load progression individually for each subject throughout the training period. The loads were adjusted so that the repetitions remained within the required range of 8-10 repetitions per set. Rest periods were set at two minutes to allow for adequate recovery between sets. Proper technique and repetition pace was supervised by the assistant researchers during each training session. Training loads and session RPE were documented in each training session to individual training logs. Each individual's training time of day was kept consistent throughout the training period.

5.4 Measurements

Participants were instructed to not consume caffeine or alcohol 12 hours prior the measurements, to avoid nicotine products and to not take part in any high intensity exercise in the 48 hours before measurements. The participants were also advised to drink 500ml water one hour before measurements to standardize hydration levels.

5.4.1 Anthropometry

Total muscle mass and whole-body fat percentage was measured by an eight-polar bioelectrical impedance device (InBody 720 body composition analyzer, Biospace Co. Ltd, South Korea). The subjects were instructed to stand upright, face forward and to have their arms abducted by approximately 20° so that the arms and trunk were not in contact. This data was used to describe the participants physical characteristics (Table 1) as well as measure the changes in body composition though out the intervention.

5.4.2 Muscle size and architecture

To measure vastus lateralis (VL) and biceps brachii muscle CSA (cm2) and thickness (mm), ultrasound images were collected using a B-mode axial plane ultrasound (model SSD-α10, Aloka, Tokyo, Japan) with a 10 MHz linear-array probe (60 mm width) (Figure 7) in extended-field-of-view mode (23 Hz sampling frequency) NextGen LOGIQ c ultrasound console (GE Healthcare UK, Ltd., Chalfont, Buckinghamshire, UK).

FIGURE 7. Linear ultrasound transducer (60 mm width) used in the study (left) and probe with custom-made probe support used in the VL CSA measurement (right)

CSA measurement of m. vastus lateralis

VL CSA images were taken from the right leg at the mid-point along the thigh. Subjects lay supine in a standardized position with their legs extended. A sculptured support was placed under the knees. To avoid rotation and movement of the limbs during the measurement, a support was placed between the ankles keeping the feet 20cm apart. To keep the feet aligned an elastic strap was placed around the feet (Figure 8). The distance from the greater trochanter to the central point of the patella was measured, from which the central value was marked as the mid-point. At this point, one axial line was marked on the skin. The measurements were documented and photos of the location of the marks on the skin were taken to ensure repeatability of the measurements at the different time points of the study. The subject was positioned on the examination table so that the marked line was aligned with the gap on the table. The gap enabled for full imaging of the VL muscle starting from the lateral intermuscular septum of the thigh.

The US images were taken after the participant had rested for 15 minutes in the supine position to allow for fluid shifts to stabilize (Berg et al. 1993). During the measurements the participant was asked to relax their muscles and keep still. A custom-made probe support was used to assist with keeping the probe perpendicular to the thigh as well as to divide pressure constantly on the skin (Figure 7). Generous amount of transmission gel was applied on the skin to ensure optimal probe-skin contact and to improve acoustic coupling. Consistent, minimal pressure was applied on the skin to avoid compression of the muscle. The probe was moved manually along the marked line starting from the lateral aspect of the thigh moving medially. The US measurement set up for the VL scans is shown in Figure 8. Three VL CSA US images were analyzed and the mean of the two closest values were taken as the CSA result.

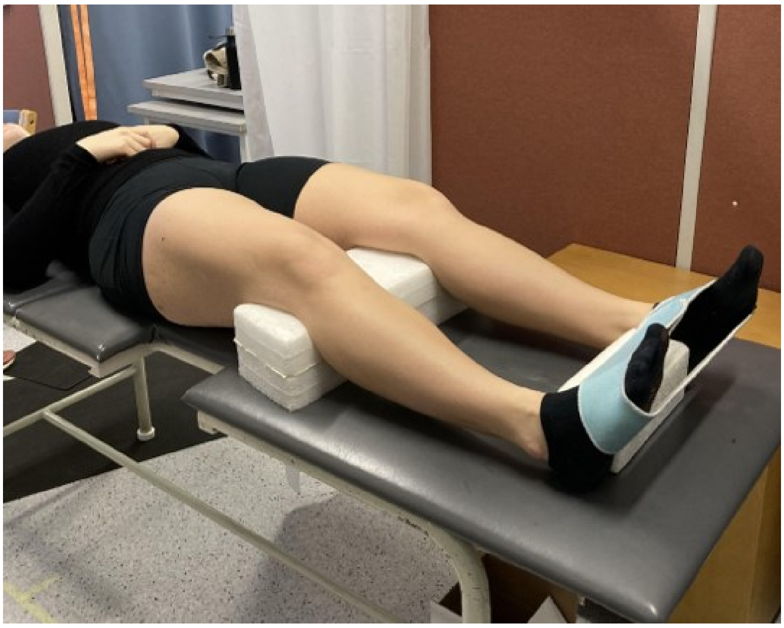

FIGURE 8. Assessment of cross-sectional area of the VL muscle with axial plane ultrasound. Gap in the examination table enabled for full imaging of the vastus lateralis muscle starting from the lateral intermuscular septum of the thigh.

Muscle thickness and pennation angle

Resting ultrasound muscle thickness and fascicle pennation angle images were taken at mid-point of femur length (location described in previous part). The probe was placed longitudinally to the thigh so that the muscle fascicles could be clearly visualized on the ultrasound screen (Figure 9). Care was taken to apply minimal pressure when placing the probe on the skin. Three still images were taken from which muscle thickness and pennation angle were measured. For each measurement, mean of the two closest values were taken as the final result.

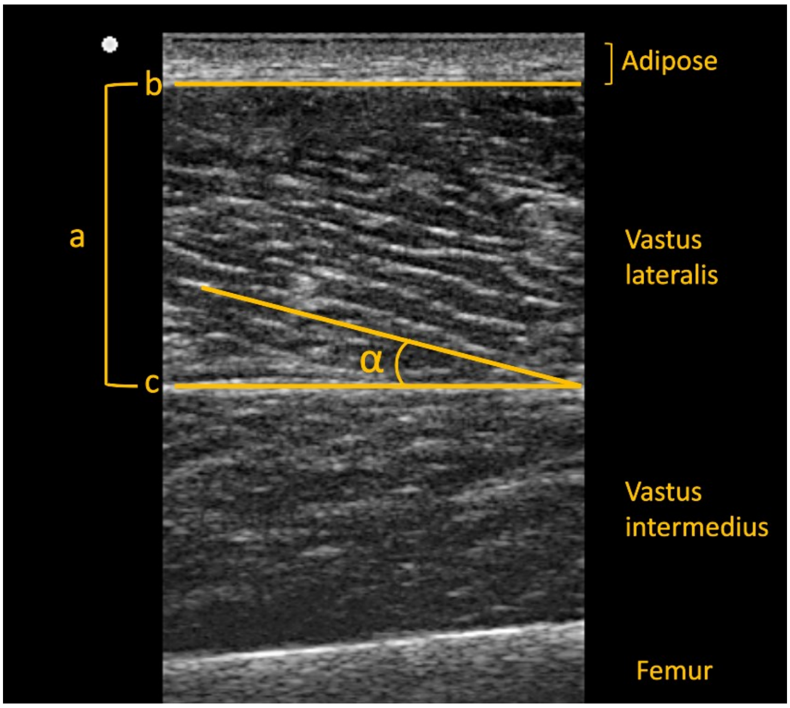

FIGURE 9. Sagittal plane US image obtained from the relaxed state vastus lateralis muscle at 50 % femur length. From the image, it is possible to measure muscle thickness (a) which is the distance between the superficial (b) and intermediate (c) aponeuroses as well as the angle of the fascicles (α).

CSA measurement of m. biceps brachii

Biceps Brachii (BB) CSA images were taken following the VL measurements. The participant was seated in a comfortable position with their right arm resting in a supported position at a 45°. For the participant to maintain a relaxed arm position throughout the measurement, the height of the arm support was adjusted according to the participants height. A sculptured support (4,5cm) was placed below the wrist. Participant held onto a tube with minimal pressure and an elastic strap was used to maintain constant arm position during the measurement. The distance from the acromion process to the central point of the elbow joint was measured from which a point was marked on the skin at 2/3 of the length distally. At this point, one axial line was marked on the skin. A strap was placed around the arm above the marked line that the probe was moved against. Care was taken to ensure that the strap did not compress the arm. Use of the strap reduced the risk of probe tilt during the measurement. Consistent and minimal pressure was applied to avoid compression of the muscle and a generous amount of transmission gel was applied on the skin to aid acoustic coupling. The probe was moved along the marked line axially from the lateral aspect medially in a slow and steady pace. The US measurement set up for the BB scans is shown in Figure 10. Three BB CSA images were analyzed and the mean of the two closest values were taken as the CSA result.

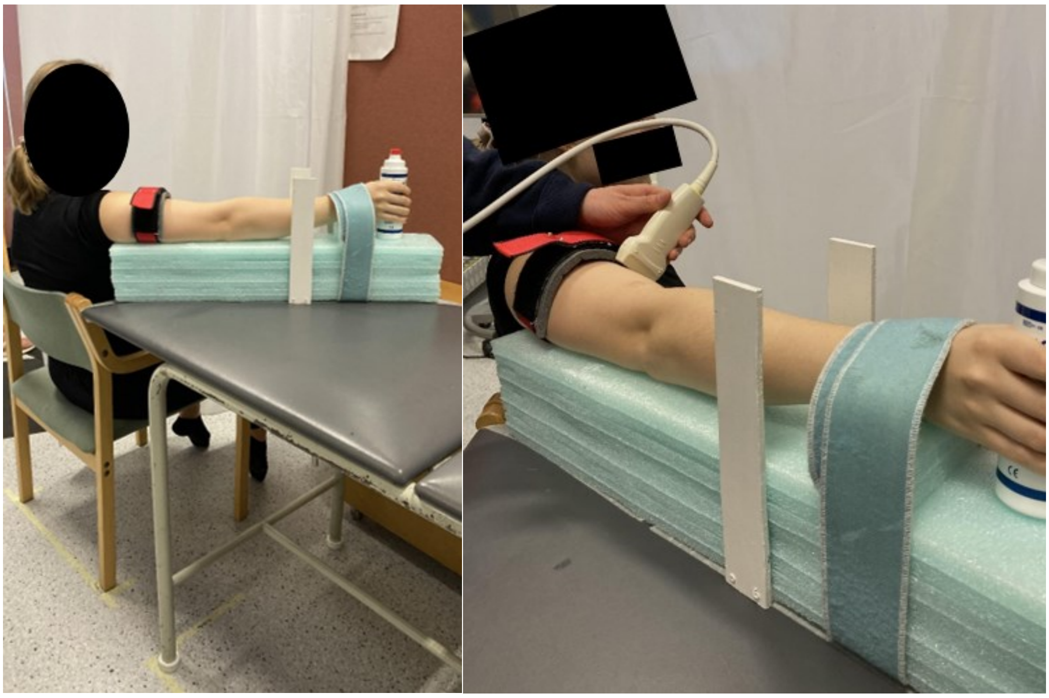

FIGURE 10. Assessment of cross-sectional area of the biceps brachii muscle with axial plane ultrasound.

The marked measurement sites on the skin were photographed to help ensure that US images were taken from the same location during each measurement point throughout the intervention. Landmarks on the skin were noted and used to ensure the exact location. Throughout the intervention period the participants were guided to maintain the marks on the skin with the use of a permanent pen. The site was re-assessed at each measurement point to ensure that the mark had not moved.

VL and BB CSA, muscle thickness and VL pennation angle were calculated using ImageJ software. The straight-line function was used to scale the images from pixels to centimeters. To calculate CSA from the scanning image, the polygon function was used to outline the periphery of the muscle carefully excluding the surrounding fascia (Figure 11 and 12). Muscle thickness was calculated as the straight-line distance between the superficial to the intermediate aponeuroses. Muscle pennation angle was measured as the angle of insertion of the fascicles into the muscle's intermediate aponeurosis (Figure 9). At each measurement point, three images were analyzed and the mean of the two closest values were taken and averaged for further analyses.

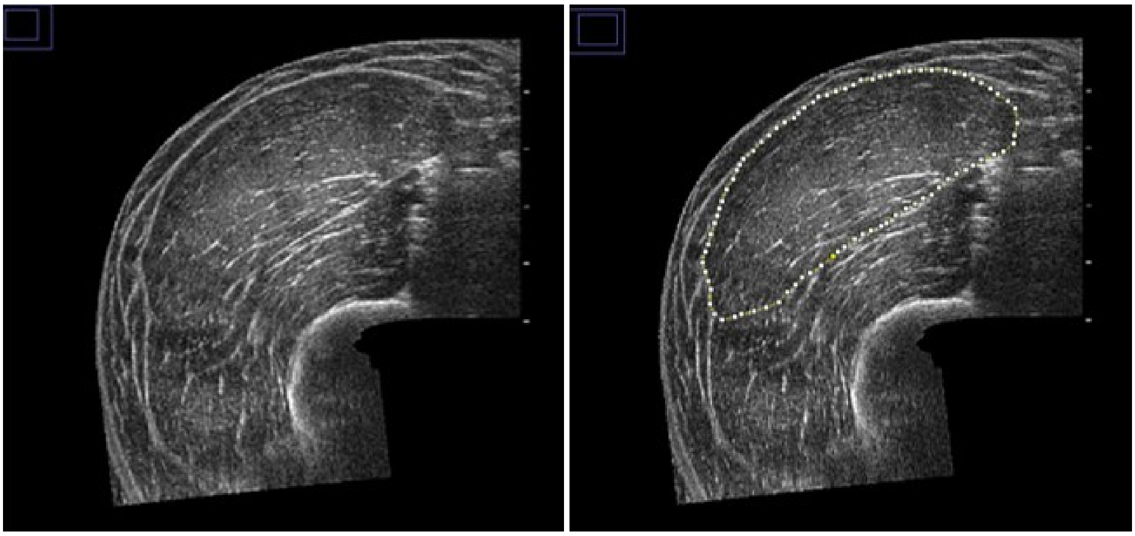

FIGURE 11. Ultrasound image of the elbow flexor muscles with the biceps brachii borders outlined (right) using the polygon function on ImageJ.

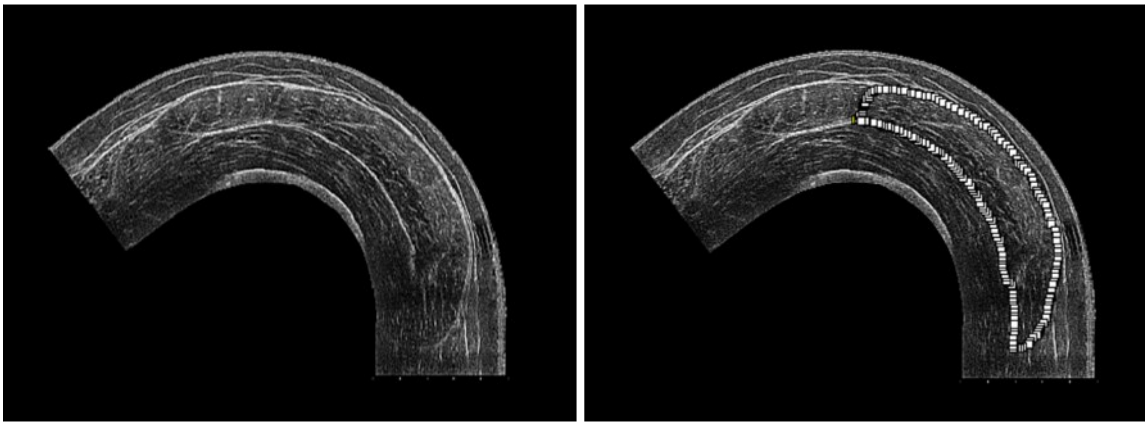

FIGURE 12. Ultrasound image of the quadriceps muscles with the vastus lateralis borders outlined (right) using the polygon function on ImageJ.

5.4.3 Maximal muscle strength

One repetition maximum (1RM) testing was performed during each measurement point before, during and after the seven-week training period as well as after the five-week de-training period. 1RM testing was measured 24-72h after the last training session. To ensure consistency in the testing, the assistant researchers were thoroughly educated on the techniques and protocol for the testing. The same warm-up that was used for the training sessions was also completed prior to testing.

One-repetition maximum elbow flexor strength testing

The maximal dynamic strength of the elbow flexor muscles was measured by determining the 1RM on the standing barbell bicep curl exercise. The subjects were positioned to stand in a supported position with a padded support adjusted behind the hips and on the scapular level. A belt around the hips secured the position. The setup of the measurement is presented in Figure 13. The grip width was self-determined by the subjects. A 7.5kg bar was used when the weight was set at less than 20kg. A 20kg bar was used when the weight exceeded 20kg.

Two warm-up sets with increasing weight were performed with one minute of rest in between the sets. In the first warm up set 10 repetitions were performed with 40-60% of estimated 1RM and in the second set five repetitions were performed with 60-80% of estimated 1RM. After the warm-up sets, weights were increased and the subject attempted to perform one complete repetition with maximal load. The subject was instructed to perform the bicep curl through full range of motion (ROM) starting with hands extended straight and bringing them to full flexion. The load was adjusted so that the 1RM could be determined to 500g accuracy ideally in three to five attempts. The attempts were separated by three minutes of rest.

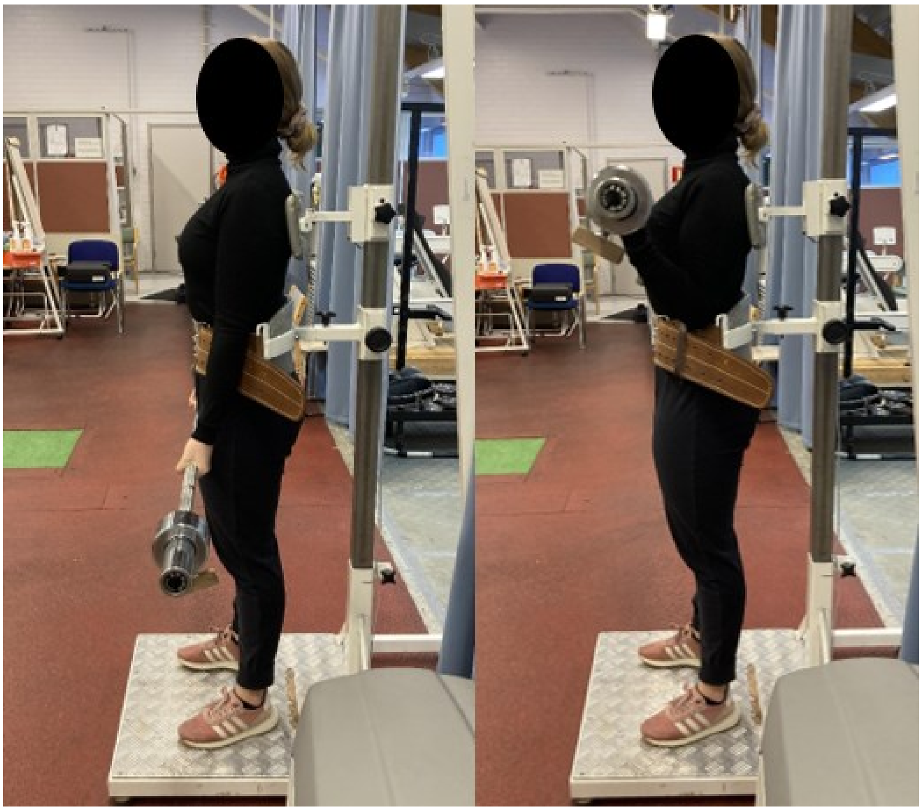

FIGURE 13. Elbow flexor strength testing

One-repetition maximum knee extension strength testing

Dynamic knee extensor muscle strength was assessed by determining the 1RM on a leg extension machine (David 210, David Health Solutions Ltd, Helsinki, Finland). The subjects were seated on the leg extension machine with their shin against the shin pad and belt secured around their hips.

Two warm-up sets with increasing weight were performed with one minute of rest in between the sets. In the first warm up set 10 repetitions were performed with 40-60% of estimated 1RM and the second set five repetitions were performed with 60-80% of estimated 1RM. After the warm-up sets, weight was gradually increased with the subject attempting to perform one complete repetition. For the 1RM the subjects were required to lift the load on the assessor's cue to a fully extended position (180° knee angle) from a starting knee angle of approximately 60° (Figure 14). The estimation of the knee angle in full extension was subjective to the assessor. Weight was adjusted so that the 1RM could be determined to 2.5kg accuracy in three to five attempts. Additional attempts were performed if needed. Rest periods were set at three minutes in between the attempts.

FIGURE 14. Knee extensor strength testing

5.5 Statistical analysis

IBM SPSS Statistics 26 (IBM Corporation, US) software and Microsoft Excel (Microsoft Corporation, US) were used to for the statistical analysis. Standard statistical analyses were used for descriptive variables (means and standard deviations (SD) and percentage changes. The reliability (ICC and CV%) and SWC was calculated for each variable.

The Shapiro-Wilk test was used to tests the normality of the data. Repeated measures ANOVA analysis was used to examine if there were any significant changes in muscle strength or hypertrophy in response to training and detraining. The post hoc tests using the Bonferroni correction was used to detect the significant pairwise differences between the different timepoints. The possible correlations between the responses in the upper and lower extremities were checked using the Pearson's correlation coefficient. The significance level was set to $p<0.05$

6. RESULTS

All participants (n=17) completed at least 12 out of 13 training sessions during the 7-week training intervention. All but one participant took part in the post training measurements and two participants did not take part in the post de-training measurements.

Intra-class correlation coefficient (ICC) coefficient of variation (CV%) was assessed for the measured variables and were found reliable (Table 2). Changes in VL CSA, VL MT, VL PA, BB CSA, KE 1RM, BC 1RM are presented below (Figures 15-20) for all time points throughout the intervention.

TABLE 2. Reliability data (ICC and CV%) of measured variables

	VL CSA	VL MT	VL PA	BB CSA	KE 1RM	BC 1RM
ICC	0.99	0.99	0.95	0.98	0.99	0.99
CV%	0.5	0.7	1.6	0.8	-	-

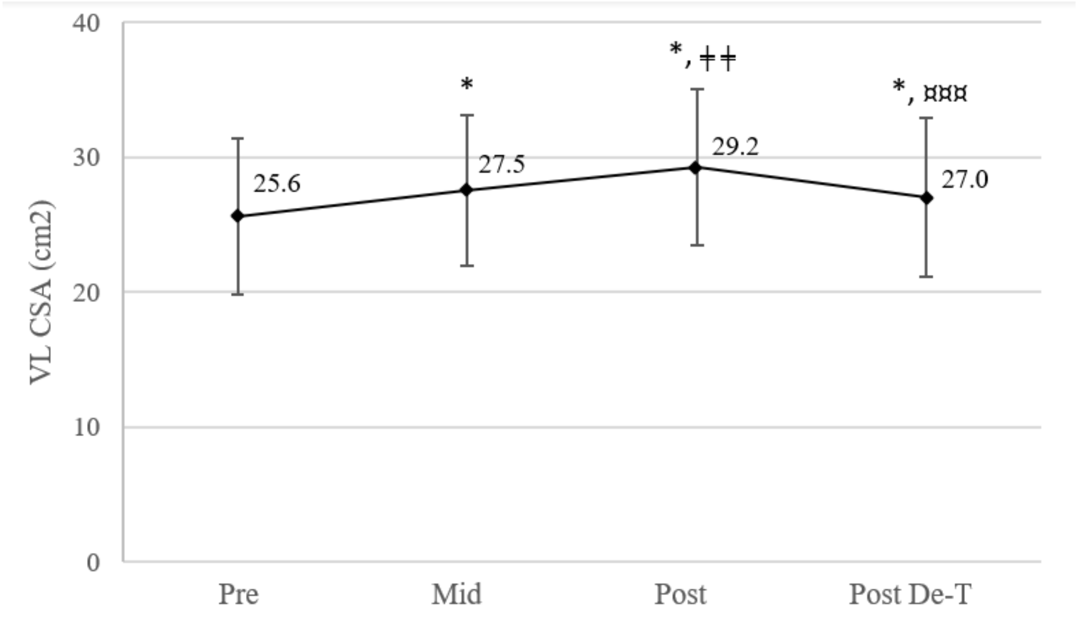

FIGURE 15. Changes in VL CSA (means and SD for absolute change) at pre (0), mid training (3.5wk), post training (7wk) and post de-training period (5wk). * VL CSA change was significant from Pre-Mid $p<0.05$; ǂǂ, from Mid-Post $p<0.05$; ¤¤¤, from Post-Post De-T $p<0.05$.

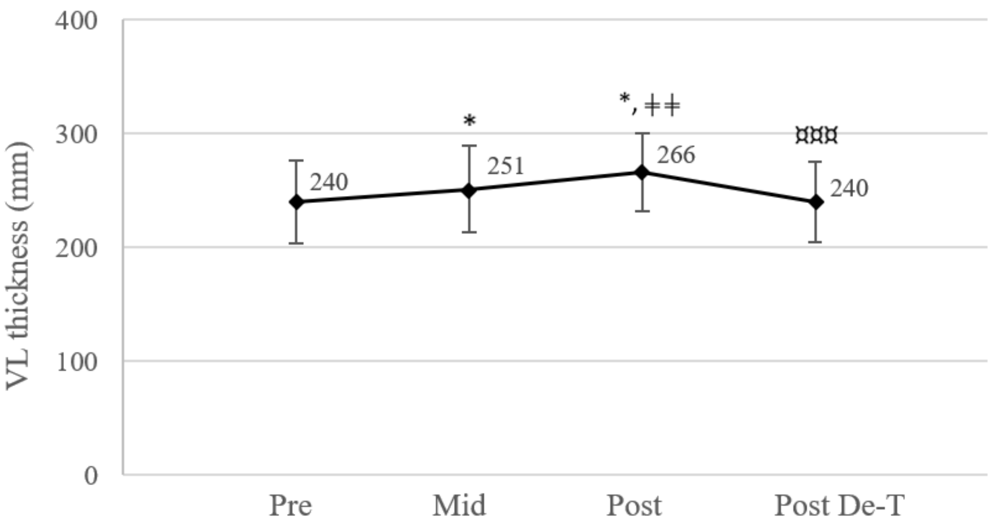

FIGURE 16. Changes in VL thickness (means and SD for absolute change) at pre (0), mid training (3.5wk), post training (7wk) and post de-training period (5wk). * VL thickness change was significant from Pre-Mid $p<0.05$; ǂǂ, from Mid-Post $p<0.05$; ¤¤¤, from Post-Post De-T $p<0.05$.

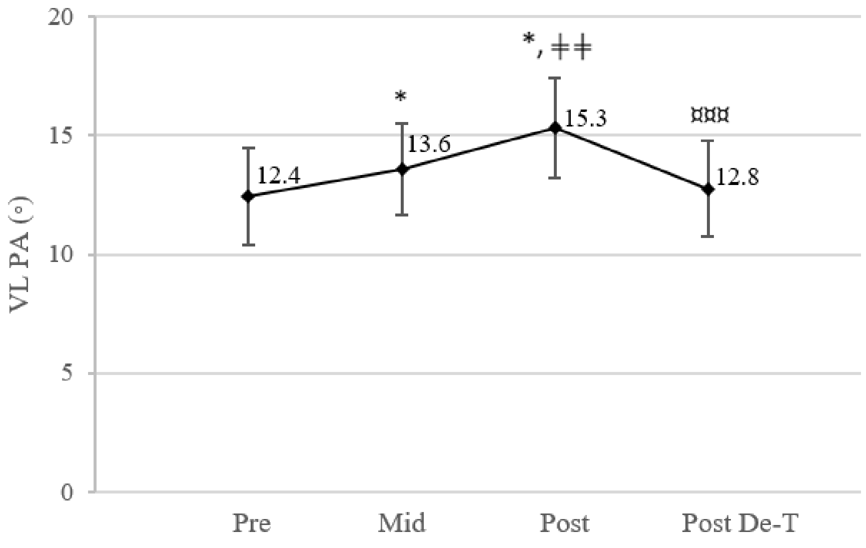

FIGURE 17. Changes in VL PA (means and SD for absolute change) at pre (0), mid training (3.5wk), post training (7wk) and post de-training period (5wk). * VL PA change was significant from Pre-Mid $p<0.05$; ǂǂ, from Mid-Post $p<0.05$; ¤¤¤, from Post-Post De-T $p<0.05$.

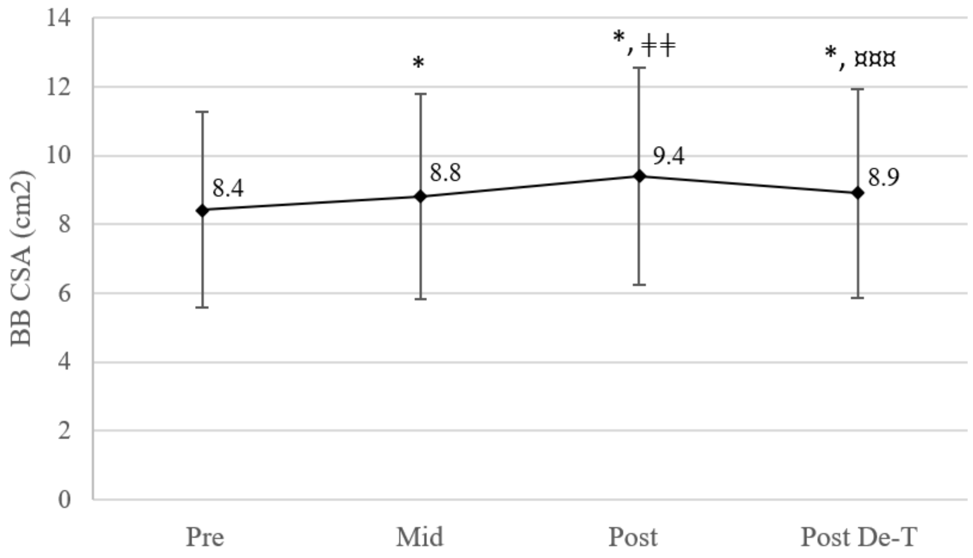

FIGURE 18. Changes in BB CSA (means and SD for absolute change) at pre (0), mid training (3.5wk), post training (7wk) and post de-training period (5wk). * BB CSA change was significant from Pre-Mid $p<0.05$; ǂǂ, from Mid-Post $p<0.05$; ¤¤¤, from Post-Post De-T $p<0.05$.

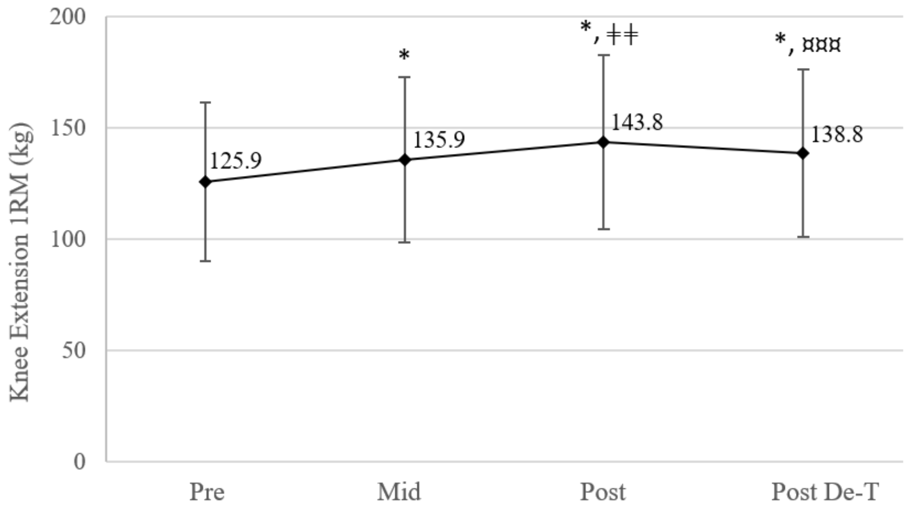

FIGURE 19. Changes in KE 1RM (means and SD for absolute changes) at pre (0), mid training (3.5wk), post training (7wk) and post de-training period (5wk). * KE 1RM change was significant from Pre-Mid $p<0.05$; ǂǂ, from Mid-Post $p<0.05$; ¤¤¤, from Post-Post De-T $p<0.05$.

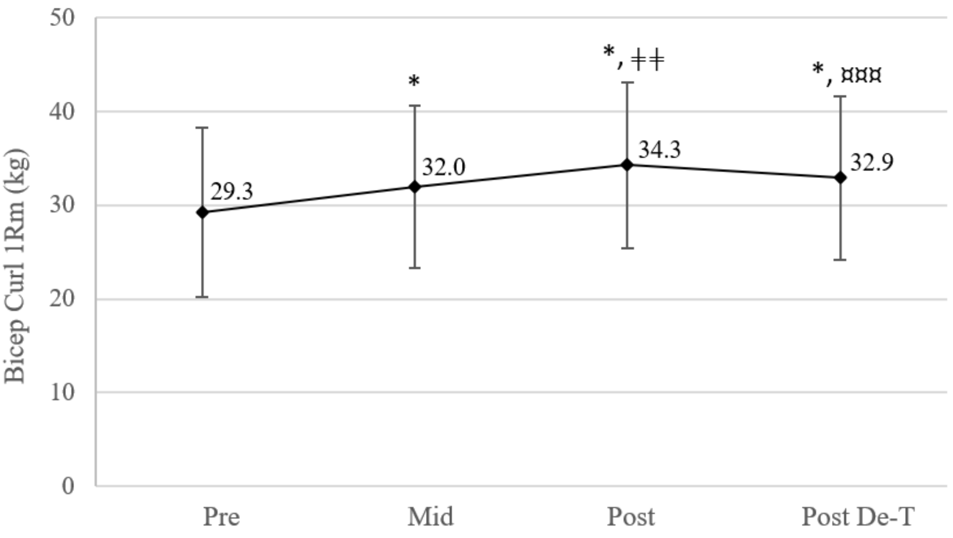

FIGURE 20. Changes in BC 1RM (means and SD for absolute change) at pre (0), mid training (3.5wk), post training (7wk) and post de-training period (5wk). * BC 1RM change was significant from Pre-Mid $p<0.05$; ǂǂ, from Mid-Post $p<0.05$; ¤¤¤, from Post-Post De-T $p<0.05$.

TABLE 3. Summary of the percentage changes at each measurement point presented for each variable

Variable	Pre-Post %	Pre-Mid %	Mid-Post %	Post-De-T %
BB CSA	11.0 ± 5.7*	3.8 ± 4.7*	6.5 ± 2.6*	-5.3 ± 2.8*
VL CSA	14.2 ± 5.9*	7.4 ± 5.7*	6.4 ± 4.1*	-7.9 ± 5.2*
VL MT	9.9 ± 6.5*	3.7 ± 4.2*	5.8 ± 4.8*	-7.9 ± 2.7*
VL PA	22.5 ± 9.3*	9.6 ± 7.9*	9.6 ± 8.4*	-20.9 ± 10.4*
BC 1RM	17.0 ± 11.6*	9.3 ± 7.7*	6.6 ± 4.8*	-4.0 ± 2.5*
KE 1RM	14.2 ± 6.5*	8.0 ± 4.7*	5.6 ± 3.0*	-3.5 ± 2.2*

* Significant change between time points ($p < 0.05$)

Selected correlations

Correlation between the responses in the upper and lower extremities

No relationship was observed between the magnitude of the responses in the lower extremities and that in the upper extremities in either maximal strength or hypertrophy. No correlation was observed between the pre-post percentage changes of BB CSA and VL CSA (r=0.17, p=0.51, n=16). Similarly, no correlation was observed between the pre-post percentage changes in BC 1RM and KE 1RM (r=0.16, p=0.55, n=15).

The individual pre-post percentage changes for 1RM strength and change in muscle CSA for the upper and lower extremities are presented in Figures 21 and 22.

Correlation between the strength and hypertrophic responses within each extremity

No relationship was observed between the responses in maximal strength and hypertrophy within each extremity. In the upper extremity, no significant correlation was observed between the pre-post percentage changes in BB CSA and BC 1RM (r=0.08, p=0.76, n=15). In the lower extremity, no significant correlation was observed between the pre-post percentage changes in VL CSA and KE 1RM (r=0.38, p=0.14, n=16).

To visualize the differences in the magnitude of the responses between the upper and lower extremities, the individual pre-post percentage changes in muscle CSA in the VL and BB are presented for each subject in Figure 21 and pre-post percentage changes in BC and KE 1RM are presented in Figure 22.

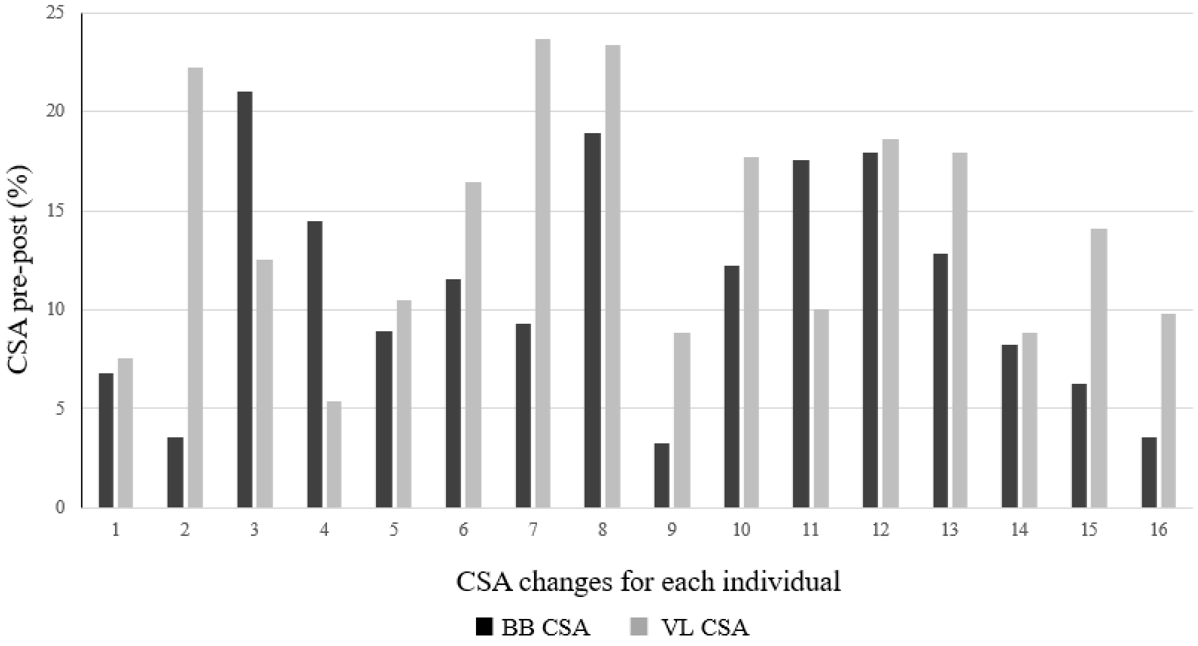

FIGURE 21. Individual pre-post % changes in BB and VL CSA presented for each subject

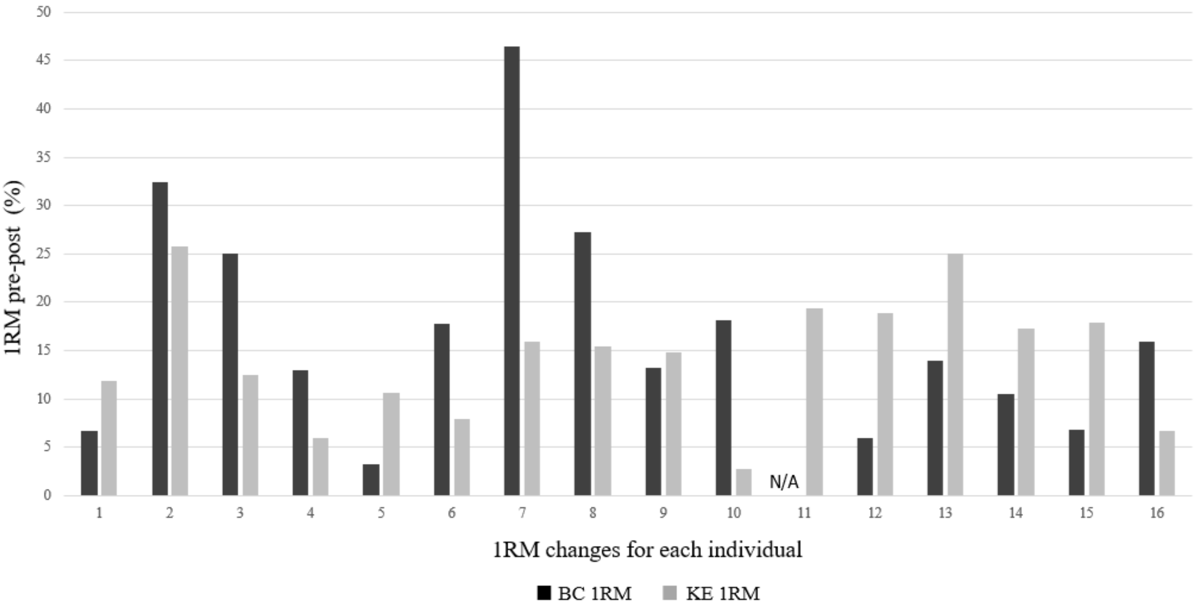

FIGURE 22. Individual pre-post % changes in BC and KE 1RM presented for each subject

Individual variability in the responses

The smallest worth-while change (SWC) (0.2 multiplied by the SD of baseline values) was used to set the lower limit of practical relevance for each variable. The SWC values for BB CSA, VL CSA, BC 1RM and KE 1RM are presented in Table 4. For each individual the absolute pre-post change is presented separately for each variable (Figures 23-26). Participants were categorized based on the lower limit of practical relevance using the SWC to either experiencing a benefit or not experiencing a benefit.

TABLE 4. Smallest worth-while change (SWC) threshold for each variable.

	BB CSA	VL CSA	BC 1RM	KE 1RM
SWC	0.62 cm2	1.46 cm2	2.21kg	8.2kg

SWC used to determine the lower limit of practical relevance for each variable.

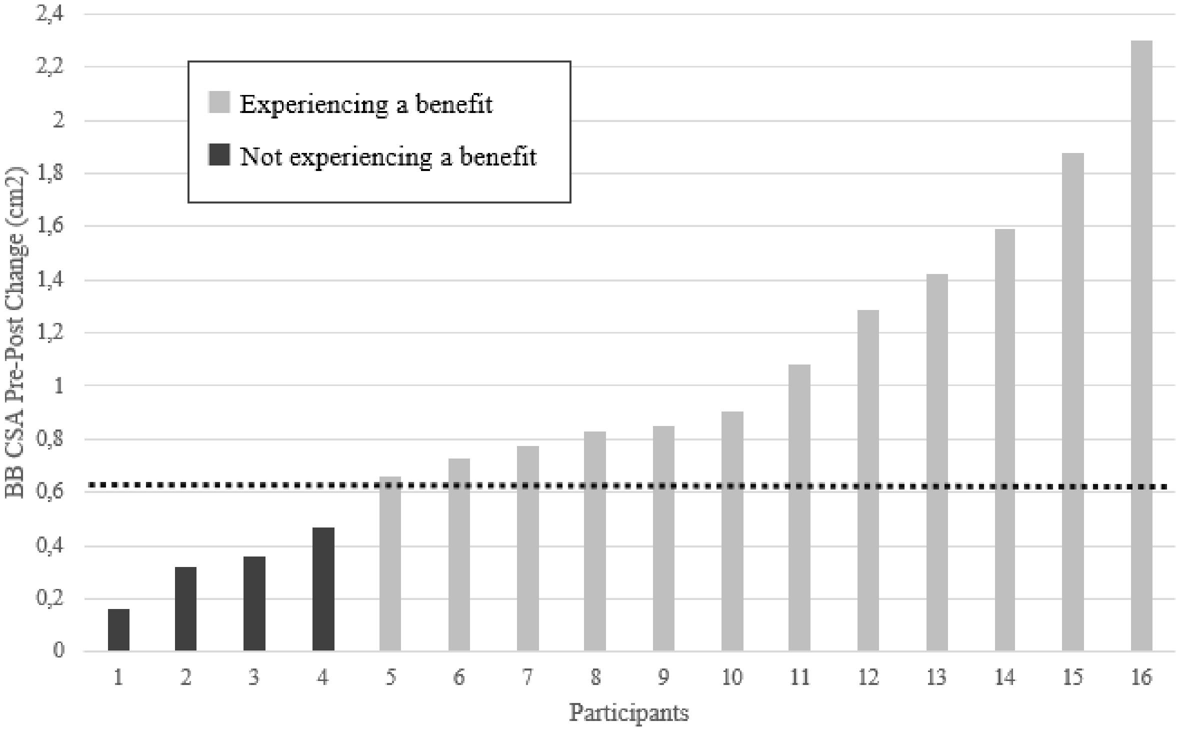

FIGURE 23. Absolute pre-post change in BB CSA for each subject. The dashed line represents the SWC for the particular variable

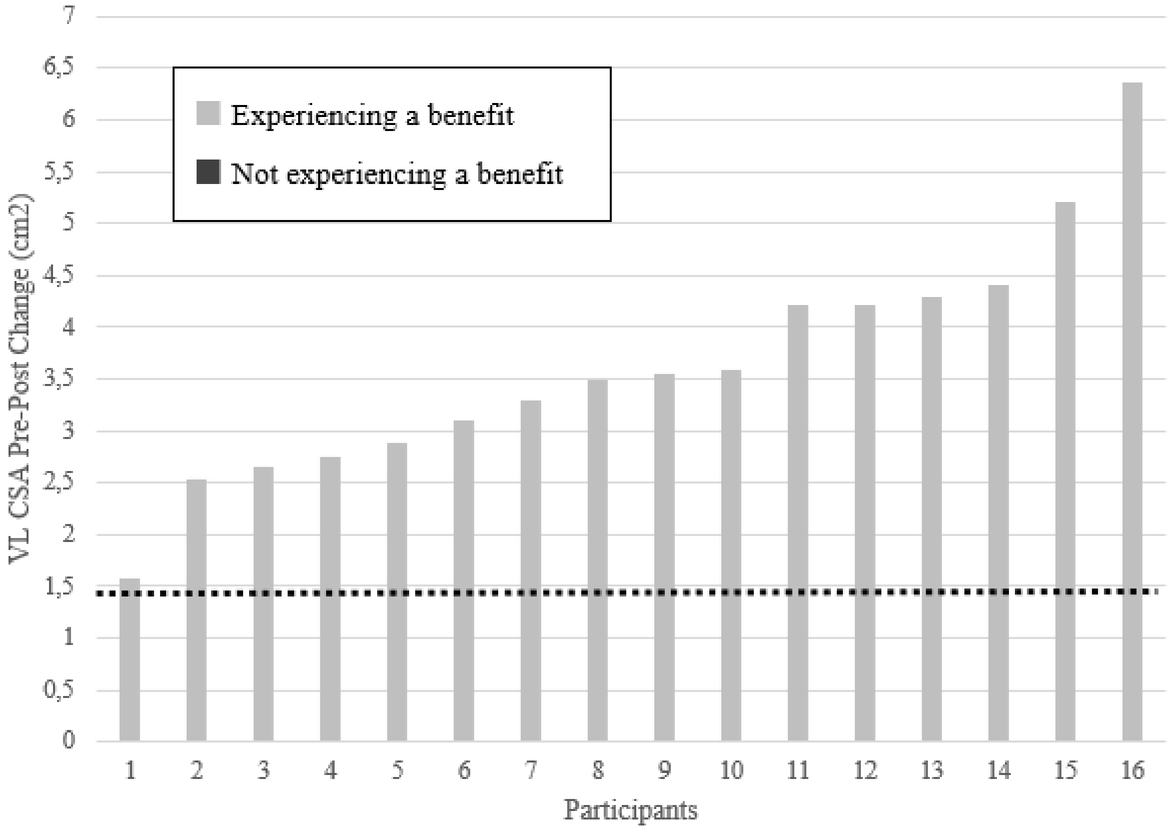

FIGURE 24. Absolute pre-post change in VL CSA for each subject. The dashed line represents the SWC for the particular variable.

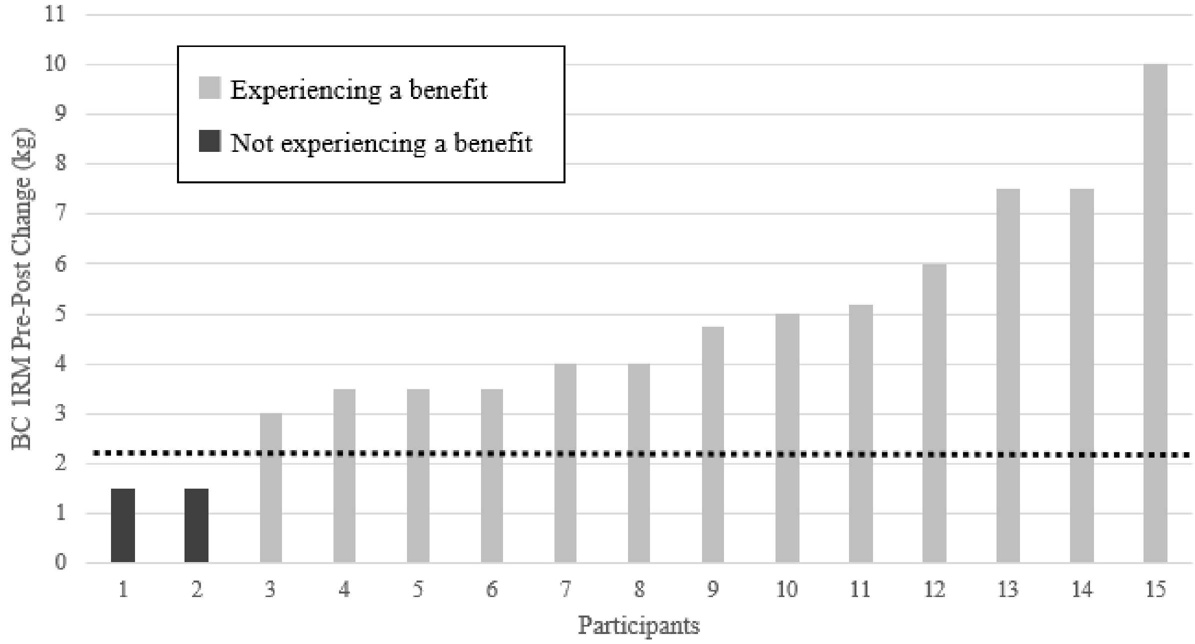

FIGURE 25 Absolute pre-post change in BC 1RM for each subject. The dashed line represents the SWC for the particular variable

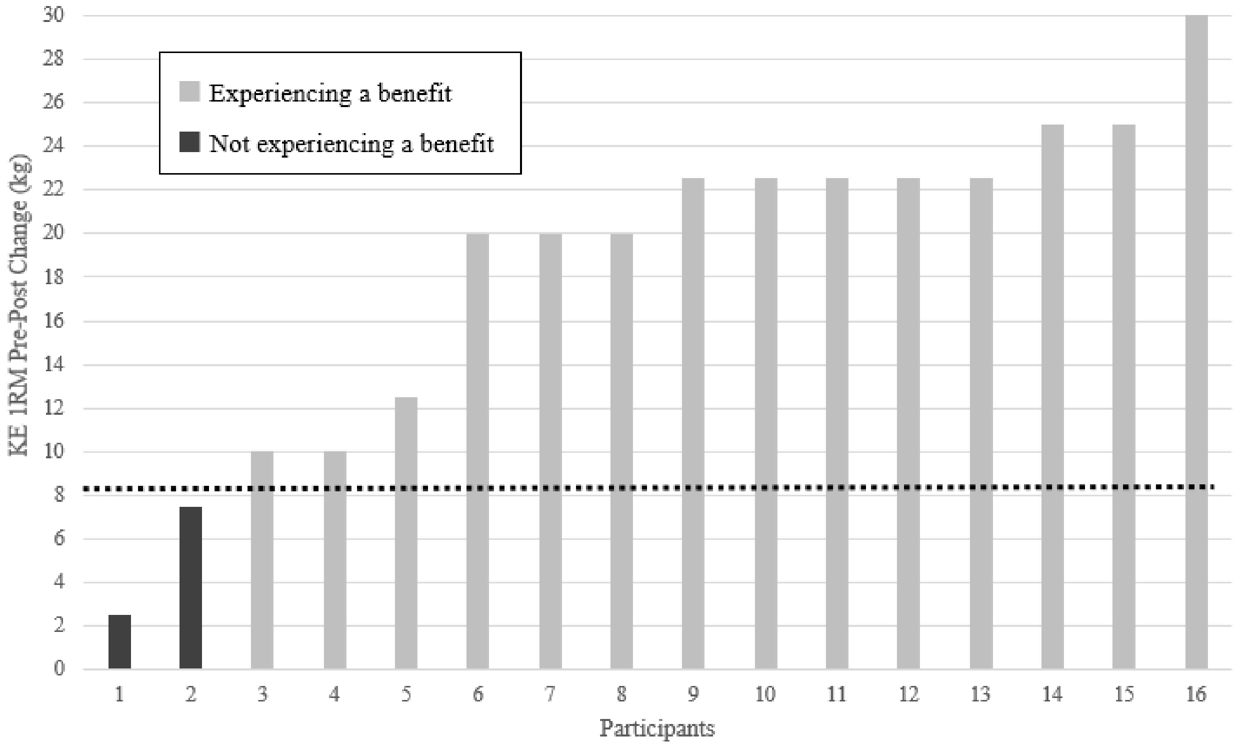

FIGURE 26. Absolute pre-post change in KE 1RM for each subject. The dashed line represents the SWC for the particular variable.

7. DISCUSSION

The aim of the study was to investigate the development of the strength and morphological adaptations in the upper and lower limbs in response to similar training regimens. Additionally, the aim was to study the heterogeneity in the resistance training induced muscle strength and hypertrophic responses in a group of previously untrained individuals. The intervention included seven weeks of progressive resistance training to the upper and lower extremities, followed by five weeks of de-training. The results demonstrated that the time course of adaptations was similar in both extremities. Maximal strength and muscle size increased significantly in both the upper and lower extremities at 3.5 weeks and further developed until the end of the seven-week training period. Individual variability was observed in the strength and hypertrophic responses however no correlations were observed in the magnitude of the responses between the upper and lower extremities.

7.1 Time course of muscle morphological and strength adaptations

Significant increases in muscle CSA were observed in BB and VL after 3.5 weeks and further increases in CSA were observed after seven weeks of resistance training. In the lower extremity, total group VL CSA demonstrated an average relative increase of 14.2% following seven weeks of resistance training. The individual pre-post percentage increases ranged from 5.3% to 23.7%. In the upper extremity, total group BB CSA demonstrated an average relative increase of 11% following seven weeks of resistance training. The individual pre-post percentage increases ranged from 3.2% to 21%.

A similar trend was observed regarding the strength gains and significant increases in maximal muscle strength were observed in the knee extensors and elbow flexors after 3.5 weeks and further increases were observed after seven weeks of resistance training. In the lower extremity, total group KE 1RM demonstrated an average relative increase of 14.2% following seven weeks of resistance training. The individual KE 1RM pre-post percentage increases ranged from 2.8% to 25.8%. In the upper extremity, total group BC 1RM demonstrated an average relative increase of 17%. The individual BC 1RM pre-post percentage increases ranged from 3.3% to 46.5%.

A five-week de-training period following the resistance training period, resulted in significant decreases in both maximal strength and muscle CSA in the elbow flexors and knee extensors. Strength and muscle CSA however remained elevated above preconditioning levels throughout the entire de-training period.

Strength gains following a period of resistance training have been studied to be a result of neural adaptations and muscle hypertrophy (Staron et al. 1994). Regarding the time course of the adaptations, neural adaptations have been considered to play a dominant role during the first weeks of training, whilst muscle hypertrophy has been understood to play a less important role (Sale, 1988). Evidence however exists that significant hypertrophy can happen during the early weeks of training given adequate intensity, frequency and volume of training (Wernbom et al. 2007). Some studies have shown that muscle growth may begin swiftly, as significant hypertrophy at the whole muscle level has been demonstrated to take place after training periods as short as 2-4 weeks in both the lower (Räntilä et al. 2021, Stock et al. 2016, Seynnes et al. 2007) and upper extremities (Jenkins et al., 2016, Krentz & Farthing, 2010). The results of this present study regarding the time course of muscle hypertrophy are in line with previous studies and indicate that significant increases in muscle size can be observed already following the first few weeks of systematic resistance training.

It is important to note that the hypertrophic gains observed within the first few weeks of resistance training in previously untrained individuals could however in part be a result of muscle edema from unaccustomed exercise (Damas et al. 2015). In the present study, US measurements were performed more than 48h after the last strength training session to decrease the possible influence of edema induced muscle swelling. Nevertheless, it is relevant to take the possible effects of muscle swelling into consideration when interpreting the results of the study.

Another notable consideration is that for practical reasons, changes in muscle morphology were measured from one muscle in the lower extremity (VL) and one muscle in the upper extremity (BB). Furthermore, muscle CSA, MT and PA were assessed from one location at ~50% of the whole muscle length in the thigh and at 2/3 of the length of the upper arm. The measured increase in muscle size at this specific site may not be representative of the morphological changes occurring as studies have demonstrated that training-induced adaptations may differ depending on the location of the muscle (Wakahara et al. 2012, Wells et al. 2014). It is possible that muscle hypertrophy might occur but is left unrecognized. The measurement locations used in this study design were appropriate to detect changes in muscle hypertrophy and architecture, however it would be beneficial to obtain measurements from more than one location to get a better understanding of the adaptations taking place.

In the lower extremities, VL PA and MT increased significantly at 3.5 weeks and further increased at seven weeks. Fascicle length was left out from the analysis due to the low PA and arrangement of the muscle fascicles not making the analysis and estimation of fascicle length reliable. Muscle architecture was assessed from the VL, however not from the BB. This was due to the poor quality of the BB sagittal plane US images resulting in poor visibility and difficulty in locating the intermediate aponeuroses making the MT measurement unreliable. The PA measurement was left out for the same reasons regarding the difficulty of analyzing the images but more importantly due to the muscle characteristics and parallel arrangement of the muscle fibers not making PA a valid and reliable measure to be obtained from the BB.

7.2 Variability in the responses

Individual variability in the responses was observed as the magnitude of the percentage increases varied between the participants in all the measured variables. Variability in the responses was also identified when categorizing the responses based on the SWC. Following the seven-week resistance training period, a portion of the subjects did not experience a benefit in maximal muscle strength in the knee extensors (n=2), maximal muscle strength in the elbow flexors (n=2) or in BB CSA (n=4) indicating that some individuals may not respond to resistance training in the same way as others. Interestingly, all subjects (n=16) achieved meaningful responses in VL CSA following the seven weeks of resistance training.

A separate control group would allow the estimation of the amount of interindividual variability when no resistance training is taking place. This would be important in order to understand whether the interindividual variability in the training group is solely resulted by the training (Hrubeniuk et al. 2021). In the present study the two-week control period was used to attain reliability trials of the measurements which allowed the assessment of measurement accuracy, as well as methodological and biological variability, in the used measures. As a separate control group was lacking in this present study, the SWC was used to set the lower limit of practical relevance as it has been found to accurately determine a meaningful change and because the test-retest reliability of the measures used in this present study were good. (Hrubeniuk et al., 2021). The calculated lower limit values are however sample specific which is important to consider when interpreting the results.

The strict categorization and use of the terms “responder” and “non-responder” have been increasingly challenged as individuals originally considered as non-responders following a period of resistance training may show improvements if the training volume is modified (Montero & Lundby. 2017), or if the training intensity is increased (Sisson et al. 2009). Because of this and due to the lack of a separate control group, the responses were split to either experiencing a benefit or not experiencing a benefit from the training intervention.

When studying the individual variability in responses it is important to consider how training status may impact the magnitude of the strength and hypertrophic response of an individual. A muscle that is trained has smaller potential to grow compared to a muscle that has not been trained before. On the other hand, a muscle that has atrophied because a period of immobilization or de-training has larger potential to grow and simply improving back to the former level will represent an increase in performance and hypertrophy if the atrophied state is considered as the baseline (Wernbom et al., 2007). This highlights the importance of acknowledging the training background of the participants to achieve reliable results as even slight variations in training status may influence the magnitude and time course of the adaptations.

The exclusion criteria in the present study included conditions relating to the training background of the subjects. Those who had engaged in regular resistance or endurance training within the past six months were excluded from the study. It may be argued that six months is insufficient to consider the participants as previously untrained and to avoid the impact the training background may have on the responses.

7.3 Upper vs lower extremities

This study aimed to assess the connection between the strength and hypertrophic responses in the upper and lower extremities. The results showed that there were no statistically significant correlations between the maximal strength or muscle hypertrophic gains between the upper and lower extremities. No statistically significant association was discovered between elbow flexor and knee extensor strength responses nor the hypertrophic responses. Also, no statistically significant association was discovered between the strength and hypertrophic responses within each extremity.

It has been noted that some muscle groups or individual muscles are more responsive training than others. One suggested explanation is the frequent use of some muscles in activities of daily living resulting in a more trained state of the muscles and therefore leaving less potential for improvements in strength and size (Wernbom et al., 2007). The elbow flexors are commonly used less than the quadriceps in activities of daily living and are therefore though to be naturally in a less trained state. Very few studies exist that compare the neuromuscular adaptations of the lower and upper extremities to similar training regimens. A study by Abe et al. (2000) observed that during a 12-week training period the increases in muscle thickness in the upper body were greater and occurred earlier compared to the lower extremity musculature. These results would support the afore mentioned theory that the muscles used frequently in daily activities would respond to training slower. A review by Wernbom et al. (2007) offers further confirmation, as the results indicate that conventional resistance training on the elbow flexors in comparison to the quadriceps show that the CSA of the elbow flexors tend to increase at a faster rate (0.20% per day) than the quadriceps (0.11% per day).

There is a lack of evidence regarding the potential differences in muscular strength gains between the upper and the lower body following resistance training (Gentil et al. 2015). Some studies have found that strength gains are larger in the upper extremities (Housh et al 1992, Abe et al. 2000), however some have reported greater strength gains in the lower extremity in comparison to the upper extremity muscles (Welle et al. 1996, Lexell et al. 1995). A challenge when interpreting the results of these studies is that the strength training protocols vary greatly and make the direct comparison of strength gains between different muscle groups difficult. A study by Gentil et al. (2015) took to compare the strength gains between elbow flexors and knee extensors in response 10 weeks of strength training of equal loading. The findings indicated similar mean strength gains in both upper and lower extremities.

The results of this present study contradict the findings of some of the previous studies as greater relative increase in muscle strength was observed in the elbow flexors (17%) than in the knee extensors (14.2%). Similarly, relative increases in muscle size were found to be greater in VL CSA (14.2%) in comparison to the BB CSA (11%). In addition to this, during the exercise intervention 11 out of 17 subjects demonstrated a meaningful change in VL CSA following 3.5 weeks of training and all subjects demonstrated a meaningful change in VL CSA after seven weeks. As for BB CSA 5 out of 17 subjects demonstrated a meaningful change in BB CSA after 3.5 weeks and 4 out of 17 subjects did not reach the lower limit of practical relevance in seven weeks. These results imply that the knee flexors are more responsive to muscle hypertrophy than the elbow flexors. The results also suggest that in the early weeks of resistance training, strength gains in the elbow flexors may be caused by neural adaptations rather than muscle morphological adaptations.

When investigating the differences in responses between individuals it is good to keep in mind the factors that may affect the responsiveness to resistance training. Gender is in general considered the most significant factor as greater muscle mass and higher levels of anabolic hormones affect the level of responsiveness (Ivey et al. 2000). In the present study, the subjects consisted of ten men and seven women. The difference in men and women regarding the natural distribution of muscle mass between the upper and lower extremities may impact the magnitude of the muscle strength and hypertrophic responses. Previous studies have indicated that gender does not influence resistance training induced responses in muscle size and strength and that both women and men demonstrated equal diversity in the responses regardless of age (Ahtiainen et al. 2016). Nevertheless, when comparing the upper and lower extremity responses it is good to keep in mind that the subjects in this present study included both sexes.

7.4 Strengths and limitations

The detailed time course of hypertrophic adaptations to strength training has not been fully established due to the large unmonitored phases in between measurement points of previous studies (Brown et al. 2017). A strength of the present study was the inclusion of the mid-measurements at 3.5 weeks assessing changes in muscle CSA and muscle architecture indicating that significant muscle morphological adaptations take place during the early stages of strength training in the upper and lower extremities. This study is among one of the few to describe and compare the time course of strength and hypertrophic adaptations of the upper and lower limbs in response to strength training and investigate whether there is a relationship between the responses in the upper and lower extremities. Additionally, this study is one of the first to measure changes in BB CSA using EFOV US imaging while most previous studies have assessed changes in MT to study resistance training induced hypertrophy in the upper body musculature. Another strength of the present study design is that the training program was standardized and designed to equally train the elbow flexors and knee extensors enabling the comparison of the strength and hypertrophic gains between the muscle groups. Additionally, the strength training was individualized and training progression was modified every week for each subject. This represented a key strength in the intervention which was reinforced by having all training sessions supervised by assistant researchers.

The relatively small sample size that included of both men and women is one limitation of this present study. The small sample size did not enable the comparison of the training induced responses between sexes. Especially, when quantifying individual responses a larger sample size would be beneficial. The lack of a separate control group is another limitation of this study especially from the perspective of investigating variability and categorizing the individual responses. The presence of a separate, independent control group would have strengthened this study and the categorization of the responses as it would have provided a more reliable estimate of true random and within-subject variation during the intervention. Another limitation related to the strength testing protocol was that the assessment of full range of motion in the knee extension was subjective to the assessor. The assessor not remaining the same throughout the intervention for each participant, may have had an impact on the reliability of the KE 1RM results.

7.5 Conclusion

The results of this study indicate that taking part in strength training with the frequency of two times per week can elicit significant changes in muscle morphology and strength in previously untrained. The training program was standardized and designed to equally train the elbow flexors and knee extensors enabling the comparison of the strength and hypertrophic gains between the muscle groups. The results demonstrated that the time course of muscle hypertrophy and strength adaptations are similar in the upper and lower extremities. Maximal strength as well as muscle size increased significantly in both the elbow flexors and knee extensors at 3.5 weeks and further developed until the end of the seven-week training period. The VL gained muscle size slightly more and at a faster rate than the BB however larger strength gains were observed in the elbow flexors than in the knee extensors. Individual variability was observed in the strength and hypertrophic responses however no correlations were observed in the responses between the upper and lower extremities.

7.6 Practical application

It is apparent that people react differently to resistance training although we standardize resistance training. This implies that some individuals are more prone to gain muscle mass and strength in certain muscle groups than others which could have valuable implications for talent detection. The lack of correlation between gains in specific muscle groups may also have important implications for training. These results support the idea that training programs should be individually tailored with frequent monitoring of the responses to detect the strengths and weaknesses and adjust the training accordingly. Future studies should further investigate the mechanisms controlling muscle growth in the different responders and study whether the dose-response relationship may impact the different responders in regard to the major training variables.

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