# EXPLOSIVE STRENGTH AND MORPHOLOGICAL ADAPTATIONS TO 7-WEEK STRENGTH TRAINING AND 5-WEEK DETRAINING

Oona Mikala

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Faculty of Sport Sciences
University of Jyväskylä
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# TIIVISTELMÄ

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Hermostollisten tekijöiden yhteys räjähtävään voimantuottoon on tunnistettu laajalti aikaisemmissa tutkimuksissa. Poikkileikkaustutkimuksissa sekä joissakin pitkittäistutkimuksissa myös lihasarkkitehtuurin on havaittu olevan yhteydessä nopeaan voimantuottoon. Räjähtävän voimantuoton sekä lihasarkkitehtuurin on havaittu adaptoituvan voimaharjoitteluun muutamissa viikoissa. Adaptaatioiden tarkkaa aikakurssia on kuvattu vain harvoissa tutkimuksissa. Tämän opinnäytetyön tarkoitus on selvittää, kuinka kauan räjähtävällä voimantuotolla ja lihasarkkitehtuurilla kestää adaptaatioitua voimaharjoitteluun, sekä onko näiden adaptaatioiden välillä yhteyksiä. Myös harjoitustauon vaikutuksia nopeaan voimatuottoon ja lihasarkkitehtuuriin tarkastellaan.

Koehenkilöt ovat aiemmin voimaharjoittelemattomia nuoria naisia ja miehiä (n=17, ikä 28±4,9 vuotta). Seitsemän viikon voimaharjoittelu koostuu pienestä määrästä plyometrisia harjoitteita sekä hypertrofisesta voimaharjoittelusta. Räjähtävää voimantuottoa mitataan kevennyshypyn nousukorkeuden sekä yhdenjalan polvenojennuksesta määritetyn isometrisen räjähtävän voimantuoton avulla. Lihasarkkitehtuurimuuttujia mitataan ultraäänikuvantamisella.

Kevennyshypyn nousukorkeus kasvoi seitsemässä viikossa 8,3±12,5 % (p<0,05). Harjoitustauon laskevan trendin seurauksena nousukorkeus ei enää tauon jälkeen eronnut lähtötasosta. Isometrisessä räjähtävässä voimantuotossa ei havaittu muutoksia. Kaikki seuratut lihasarkkitehtuurimuuttujat adaptoituivat harjoitteluun jo kolmessa ja puolessa viikossa. Koko seitsemän viikon harjoitusjakson aikana vastus lateraliksen poikkipinta-ala kasvoi 14,2±5,9 % (p<0,05), lihaspaksuus 9,9±6,5 % (p<0,05) ja pennaatiokulma 22,5±9,3 % (p<0,05). Kaikissa lihasarkkitehtuurimuuttujissa tapahtui merkittävä lasku harjoitustauon seurauksena. Viiden viikon harjoittelutauon seurauksena poikkipinta-alan muutos oli -9,0±6,3 % (p<0,05), lihaspaksuuden -8,8±3,4 % (p<0,05) ja pennaatiokulman -20,9±10,4 % (p<0,05). Räjähtävän voimantuoton harjoitusadaptaatiot eivät olleet yhteydessä lihasarkkitehtuurin muutoksiin.

Räjähtävän voimantuoton varhaisia adaptaatioita selittävät muut tekijät kuin lihasarkkitehtuurin muutokset. Kolme ja puoli viikkoa on riittävä aika harjoittelusta seuraavien lihasarkkitehtuurin muutosten saavuttamiseksi aiemmin voimaharjoittelemattomilla. Viiden viikon harjoitustauko aiheuttaa kevennyshypyn nousukorkeudessa laskevan trendin sekä merkitsevän laskun lihasarkkitehtuurin adaptaatioissa.

Asiasanat: isometrinen räjähtävä voimantuotto, kevennyshyppy, voimaharjoittelu, lihasarkkitehtuuri, adaptaatioiden aikakurssi, harjoitustauko

# ABSTRACT

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The connection between neural properties and explosive strength has been widely demonstrated in previous studies. In cross-sectional as well as in some longitudinal studies muscle architecture has also been reported to be connected to rapid force production. Both explosive strength and muscle architecture has been reported to adapt to training within weeks. However, the precise time-course of adaptations is seldom described. The purpose of this master's thesis is to examine the time-course of explosive strength and morphological adaptations and possible correlations between those adaptations. The effects of detraining period on training induced adaptations are also studied.

The subjects of the study are previously untrained young men and women (n=17, age 28±4.9 years). The 7-week training intervention consists of low volume of plyometric exercises and hypertrophic type strength training. Explosive strength is measured as countermovement jump height and isometric rate of force development. Muscle architecture is studied with ultrasound imaging.

The countermovement jump height increased in seven weeks by 8.3±12.5% ($p<0.05$). Detraining caused a decreasing trend in jump height resulting it to be no longer different from pre-training level. In rate of force development there was no change during the intervention. The cross-sectional area, muscle thickness, and pennation angle of vastus lateralis increased both during the first and latter 3.5 weeks of the intervention. The total increase in response to 7 weeks of training was 14.2±5.9% ($p<0.05$) for cross-sectional area, 9.9±6.5% ($p<0.05$) for muscle thickness, and 22.5±9.3% ($p<0.05$) for pennation angle. There was a significant decrease in all muscle architecture variables in response to detraining. The 5-week detraining period caused a decrease of 9.0±6.3% ($p<0.05$) in cross-sectional area, a decrease of 8.8±3.4% ($p<0.05$) in muscle thickness, and a decrease of 20.9±10.4% ($p<0.05$) in pennation angle. The adaptations of explosive strength didn't correlate with the adaptations of any of the studied muscle architecture variables.

The early adaptations in explosive strength appear to be connected to other aspects than changes in muscle architecture. Three and half weeks is enough to elicit significant training induced adaptations in muscle architecture in previously untrained subjects. Five weeks of detraining causes a decreasing trend in jumping performance and significant decreases in morphological adaptations.

Key words: rate of force development, countermovement jump, resistance training, muscle architecture, time-course of adaptations, training cessation

# ABBREVIATIONS

| | |
|---|---|
| CMJ | counter movement jump |
| CSA | cross-sectional area |
| DJ | drop jump |
| EFOV | extended field-of-view |
| FL | fascicle length |
| MT | muscle thickness |
| PA | pennation angle |
| pRFD | peak rate of force development |
| RF | rectus femoris |
| RFD | rate of force development |
| SJ | squat jump |
| VI | vastus intermedius |
| VL | vastus lateralis |
| VM | vastus medialis |

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# 1 INTRODUCTION

Explosive strength is a physical property describing one's ability to voluntarily product high forces in a limited time frame (Mafiuletti et al. 2016). The importance of varying neural aspects to fast force production is relatively widely studied, and for example the integral role of recruitment speed of motor neurons (DelVecchio et al. 2019, Dideriksen et al. 2019), discharge rate of motor neurons (DelVecchio et al. 2019), and cortical drive (DelVecchio et al. 2019) has been identified. It has been demonstrated that the ability to voluntarily activate muscle during rapid contractions appears to mainly influence explosive force production in isometric movements but, however, muscles intrinsic contractile properties do affect as well (Folland et al. 2014).

Muscle architecture comprises a range of variables characterising the arrangement of muscle's structural parts and its size (Blazevich et al. 2006a). Muscle thickness (Coratella et al. 2020; Secomb et al. 2015), fascicle length (Coratella et al. 2020), and pennation angle (Secomb et al. 2015) have been found to correlate with explosive strength in cross-sectional studies. Both explosive strength and muscle architecture are known to be affected by different types of training interventions, and there have been studies aiming to detect if adaptations in muscle architecture are connected to adaptations seen in explosive strength (Stasinaki et al. 2019; Zaras et al. 2016). However, the knowledge of the topic is still far from comprehensive. Currently, the understanding of the time-course of explosive strength and morphological adaptations is limited as well.

The aim of this study is to describe the time-course of explosive strength adaptations to combined resistance training and low volume of plyometric exercises and following detraining in previously untrained adults. To characterize the time-course of adaptations explosive strength is measured before, in the halfway, and after the 7-weeks training intervention. Changes in muscle architecture are assessed at the same time-points and possible connections to explosive strength adaptations will be examined. Time needed to elicit significant changes in variables describing explosive strength and muscle architecture will be verified. In conclusion the novel aspects in the present study design include that a longitudinal design is employed to detect connections between muscle architecture and explosive strength, the time-course of morphological and strength adaptations is studied, and the effects of detraining are tracked.

# 2 EXPLOSIVE STRENGTH

Muscular performance is generally, as well as explosive force production, determined by the neural activation of the muscle together with the contractile properties of the motor unit (Dideriksen et al. 2019). Explosive strength as a property can be characterized as an ability to effectively increase force from low or resting level with a voluntary contraction (Maffiuletti et al. 2016). The relative importance of different neural and contractile properties has been lately studied both *in vivo* and based on computational model. The examination of the behaviour of motor neurons during explosive contractions indicated that the recruitment speed and discharge rate of motor neurons largely explain interindividual variation in ability for rapid force production (Del Vecchio et al. 2019). Additionally, the importance of the cortical drive to the motor neurons prior to the force generation was recognized. (Del Vecchio et al. 2019) Dideriksen et al. (2019) examined the relative importance of the velocity of motor unit recruitment, motor unit discharge rate, and motor unit force twitches with a computational model and showed that the rate of motor unit recruitment appears to mainly limit explosive force production.

Explosive strength is a reasoned research topic in different populations. Ability to produce force fast is a key element in multiple sports and it is emphasized when the time for force production is limited as it is for example in sprinting (Brady et al. 2020; Thomas et al. 2015), jumping (Townsend et al. 2019), and throwing (Anousaki et al. 2015). Additionally, explosive strength is related to measures of balance in different age-groups (Muehlbauer et al. 2015) and is thus a relevant variable to be studied also in non-athletic populations.

## 2.1 Measuring explosive strength of lower extremities

Both isometric and dynamic strength testing have been implemented for decades to assess maximal and explosive force production of different populations (Wilson & Murphy 1996). In isometric strength testing a subject produces force against an immovable resistance and the force can be measured with either force plate, strain gauge, or cable tensiometer. Both single-joint and multi-joint explosive isometric contractions have been shown to possibly have good reliability. However, the role of familiarization and careful standardization has been emphasized to acquire acceptable reliability, as most subjects may not be previously familiar with strength testing involving isometric contractions. In comparison to dynamic testing, isometric testing has been suggested to have a poorer ability to differentiate athletes of different performance levels. Possible explanations for poorer ecological validity of isometric testing include that stretch-shortening cycle cannot be used, the one joint angle chosen for isometric testing scarcely represents comprehensively the whole range of movement, and the activation patterns of a muscle may differ between contraction types. (Wilson & Murphy 1996)

As already mentioned, dynamic movements are regarded suitable for assessing sport-specific performance. Most typical dynamic testing modalities include isokinetic and isoinertial movements. In isokinetic movements the velocity of movement is constant whereas in isoinertial movements the total load in turn is unchanged during the movement. (Wilson & Murphy 1996). Counter-movement jump (CMJ) is a dynamic test frequently used to assess explosive strength of lower extremities (Van Hooren & Zolotarjova 2017). CMJ and other vertical jump tests can be implemented with different measuring devices including contact mat, accelerometer-based sensors, photoelectrical cell systems, and force plates, of which force plate is considered as a golden standard (Steinman et al. 2019).

The relationship between dynamically and isometrically measured explosive strength has been studied with cross-sectional design. Isometric explosive strength measured from isometric knee-extension and dynamic explosive strength measured from two vertical jumps, CMJ, and squat jump (SJ), showed a high positive correlation. The correlation for isometric explosive strength and CMJ was 0.86 and for isometric explosive strength and SJ 0.84. (De Ruiter et al. 2006). Thus, it is plausible that there are common underlying mechanisms between the two types of explosive contractions. De Ruiter et al. (2006) reported that explosive strength in both isometric and dynamic test was correlated with muscle activation during early phase of the contraction in the type of contraction in question. However, as the correlation between values describing explosive strength measured from movements with different contraction types is not perfect there are also distinct mechanisms contributing to them. Thus, it is reasonable to utilize both types of explosive strength testing to develop comprehensive understanding of possible adaptation mechanisms.

### 2.1.1 Isometric explosive strength

Rate of force development (RFD) is a variable that is used to characterize the ability to produce force in the beginning of contraction (figure 1) (Maffiuletti et al. 2016). Thus, it is seen as an indicator of explosive isometric force when measured from contractions that don't include change in muscle length. RFD is calculated by dividing change in either force or torque by change in time and is therefore related to the steepness of the force-time curve (Maffiuletti et al. 2016).

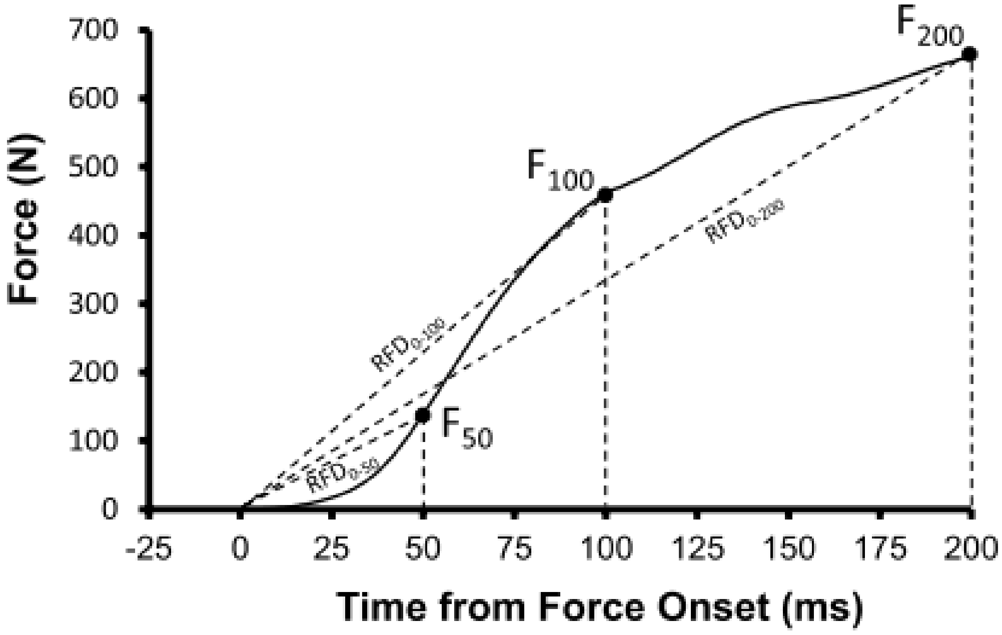

FIGURE 1. Force-time curve. (Maffiuletti et al. 2016)

RFD is not a single variable, but it can be calculated in different ways. There are three commonly used types of RFD variables. RFD can be determined for different time-intervals from the beginning of the contraction as in figure 1. Alternatively, RFD can be calculated for the steepest part of the force-time curve typically at precision of 1 to 60 milliseconds, and then the variable is called peak RFD (pRFD) (Drake et al. 2019, Parry et al. 2020, Garcia et al. 2018). Average RFD is used when rate of force development is calculated for particular part of the contraction that is not defined with predetermined timeframe. In isometric movements average

RFD is typically calculated from onset of the contraction to the point where peak force is reached (Drake et al. 2019). RFD variables determined for particular time-intervals can be furthermore divided to early and late phase RFD. Depending on the study in question the classification somewhat differs. Early RFD has been defined to cover force-time curve from onset of the contraction to 100 ms (Andersen et al. 2010) or to 150 ms (Drake et al. 2019), whereas late RFD is considered to include RFDs for longer time intervals from 150 ms (Drake et al. 2019) or 200 ms (Andersen et al. 2010). Late phase RFD typically correlates with maximal force (Coratella et al. 2020).

The reliability of RFD from isometric movements has lately been relatively widely studied. RFD has been reliably (ICC > 0.80, CV% < 10.0) measured for example from isometric mid-thigh pull (Brady et al. 2018, Brady et al. 2020, Dos Santos et al. 2017), isometric squat (Drake et al. 2019, Brady et al. 2018, Brady et al. 2020), and isometric knee-extension (Courel-Ibáñez et al. 2020). However, there are also studies demonstrating poor reliability of RFD when measured from above-mentioned movements (Keogh et al. 2020, Thomas et al. 2017). Based on previous studies characterizing the reliability of RFD it can be concluded that movement type (Thomas et al. 2017), joint angle (Drake et al. 2019), verbal instruction given for contraction (Drake et al. 2019), and the RFD variable measured (Dos Santos et al. 2017, Drake et al. 2019, Brady et al. 2020) are possible factors influencing the reliability of measurement. It appears to be important to select training-specific testing movement, emphasize fast force production in verbal instructions, and prefer late-phase RFD variables.

Isometrically measured explosive strength characterized as RFD has been shown to correlate with different sport-specific performance variables. Late-phase RFDs have been found to correlate with sprint times (Brady et al. 2020, Townsend et al. 2019), jumping height (Townsend et al. 2019), throwing performance (Anousaki et al. 2018), and weightlifting performance (Townsend et al 2019, Beckham et al. 2013), for example.

In untrained subjects, inter-individual differences in RFD have been shown to be relatively high (Folland et al. 2014). The difference appears to be highest in the beginning of the contraction. In RFD defined for first 50 ms of the contraction the difference between highest and lowest values was 13-fold (CV 48%). The difference between subjects decreased (CV 23%) throughout the contraction (150 ms). There were significant inter-individual differences even when RFD was normalized to subjects maximal voluntary contraction (MVC). Relative RFD for 50 ms varied between 4-30% of subject's MVC (CV 38%) and for 150 ms between 58-88% of subject's MVC (CV 8%). MVC was found to be less variable between subjects in comparison to RFD and highest value was only 2.3-fold compared to lowest. Electrically stimulated octet force for 50 ms varied less (CV 23%) between subjects than RFD. Muscle activity measured with EMG varied between subjects to same extent as RFD (50 ms CV 38%, 150 ms CV 23%). (Folland et al. 2014). Thus, it can be hypothesised that relatively high inter-individual variability in RFD is mainly due to differences in ability to voluntarily activate agonist muscles and secondarily due to muscles intrinsic contractile properties.

### 2.1.2 Dynamic explosive strength

CMJ is frequently applied to assess dynamic explosive strength. In CMJ a subject performs a rapid downward movement followed by vertical jump. Thus, CMJ reflects the capacity of lower extremities to produce force in restricted amount of time as well as one's effectiveness to use stretch shortening cycle (Van Hooren & Zolotarjova 2017). Drop jump (DJ) and squat jump (SJ) are other relatively widely used tests to measure dynamic explosive force (Fernandez-Gonzalo et al. 2014). Typical variables measured from CMJ comprise mean force, mean power, and peak force of concentric phase, flight time, jump height and peak power (Heishman et al. 2020). If a single variable is chosen typically either flight time or jump height is reported as it describes performance outcome of the jump.

It has been suggested that more detailed analysis of key factors including power, force, velocity, and displacement in relation to time is required to get a comprehensive image of causes of adaptations and mechanisms behind increased performance in CMJ (Cormie et al. 2009). However, the reliability of all alternative variables has not been shown to be sufficient (ICC > 0.80, CV% < 10.0). In the study by Heishman et al. (2020) the reliability of concentric and eccentric duration as well as concentric and eccentric RFD was poor. When CMJs executed with and without arm swing were compared there was a trend for slightly lower reliability of key variables (jump height, flight time, mean force, and mean power) when arm swing was allowed, which was reasoned to be due to better isolation of impact of lower extremity function in jumps with controlled arm position (Heishman et al. 2020). Thus, to enhance the reliability of variables measured from CMJ controlled arm position can be suggested. Still, it needs to be noted that arm swing during CMJ enhances performance in elite athletes (38%, Vaverka et al. 2016) as well as in less trained subjects (19%, Lees et al. 2004) in comparison to CMJ with controlled arm position. The increase in jump height as a result of arm swing appears to be due to higher velocity and height of the centre of mass at take-off (Lees et al. 2004).

# 3 EXPLOSIVE STRENGTH ADAPTATIONS TO STRENGTH TRAINING AND DETRAINING

The effects of varying strength training protocols of different lengths to explosive strength have been relatively widely studied in untrained subjects. In previous studies the effects of both conventional (Aagaard et al. 2002; Peltonen et al. 2018b), isometric (Oliveira et al. 2016; Tillin et al. 2012; Tillin & Folland 2014), and eccentric only (Fernandez-Gonzalo et al. 2014; Stasinaki et al. 2019) strength training as well as plyometric training (Cormie et al. 2009) to both isometrically and dynamically measured explosive strength have been examined. Studies of the topic will be reviewed below so that the effects of shortest training interventions are discussed first to characterize the role of time to the extent of adaptations and thus outline a rough time-course of explosive strength adaptations. Also, the effects of detraining on explosive strength adaptations will be reviewed.

## 3.1 Adaptations to training

As short training periods as 4 weeks have shown to induce significant adaptations in maximal and explosive strength (Table 1). Tillin et al. (2012) studied the effects of 4 weeks isometric knee-extension training on force production. Previously untrained subjects trained 4 times a week, and the intervention consisted of explosive isometric contractions. Maximal force increased by 11%, RFD for first 50 ms (RFD50) by 54%, RFD for first 100 ms (RFD100) by 15%, and RFD for first 150 ms (RFD150) by 14%. RFD relative to maximal force increased only for first 50 ms (37%). Besides voluntary force also electrically stimulated octet force increased after training period at 50 ms (7%) and 100 ms (10%). (Tillin et al. 2012). In a later study by Tillin & Folland (2014) the effects of similar isometric explosive training were compared to those of 4 weeks maximal isometric training. Maximal force increased more after maximal (21%) versus explosive (11%) training protocol, but explosive force measured as RFD 50, RFD100, and RFD150 increased significantly only after explosive training (70%, 16%, and 14%, respectively). It was reported that maximal training increased the muscle activity during maximal force production while explosive training caused an increase in muscle activity in the early phase of force production. (Tillin & Folland 2014). It can be concluded that 4 weeks of explosive isometric training involving rapid maximal contractions is sufficient to elicit significant adaptations in explosive strength. Such early adaptations can be hypothesised to be due to enhanced neural drive to muscles in the early phases of contraction.

TABLE 1. Minimum time needed for a range of explosive strength adaptations.

| Explosive strength variable | Weeks of training needed to elicit significant adaptations/sessions in total | Training modality | Percent change | Study |
|---|---|---|---|---|
| CMJ height | 10 weeks/20 sessions | Combined eccentric strength training and plyometrics | 15% | Methenitis et al. 2020 |
| DJ height | 6 weeks/15 sessions | Eccentric strength training | 3% (men),<br>11% (women) | Fernandez-Gonzalo et al. 2014 |
| SJ height | 6 weeks/15 sessions | Eccentric strength training | 4% (men),<br>8% (women) | Fernandez-Gonzalo et al. 2014 |
| RFD100 | 4 weeks/16 sessions | Isometric explosive strength training | 15% | Tillin et al. 2012 |
| RFD150 | 4 weeks/16 sessions | Isometric explosive strength training | 14% | Tillin et al. 2012 |
| RFD200 | 6 weeks/12 sessions | Eccentric strength training | 12% | Stasinaki et al. 2019 |
| RFD250 | 6 weeks/12 sessions | Eccentric strength training | 12% | Stasinaki et al. 2019 |

CMJ, countermovement jump; DJ, drop jump; SJ, squat jump; RFD, rate of force development.

Interestingly, a 6-week training period of isometric maximal knee extension with long contraction time increased RFD10 and RFD20 (22-28%), but not later phase RFD (Oliveira et al. 2013), which somewhat contradicts to the results of Tillin & Folland (2014) that demonstrated no change in RFD after maximal isometric training. However, the increase in maximal force was similar (19%) (Oliveira et al. 2013). The different response of RFD to isometric training employing contractions of several seconds can be potentially explained by different instructions for contractions. In the study by Tillin & Folland (2014) the force was gradually increased and then maintained while the subjects in the study by Oliveira et al. (2013) were instructed to contract as fast as possible and then to hold the achieved force. Thus, it seems to be possible to elicit adaptations both in RFD and maximal force in relatively short period of time as long as the training program includes fast force production.

Similar to the findings of Tillin & Folland (2014) only explosive strength training but not maximal strength training induced significant increase in RFD when eccentric only training was carried out for six weeks (Stasinaki et al. 2019). Increases were seen for RFD100, RFD150, RFD200, and RFD250. Dynamic explosive strength was assessed with CMJ. Jump height did not change significantly after either of the training programs. Six weeks of slow maximal strength training even decreased the power production during CMJ (6,8%). (Stasinaki et al. 2019). Likewise, when the effects of a 6-week eccentric overload training intervention to dynamic explosive strength were assessed with CMJ, no significant changes were detected albeit there was a slight positive trend (3% and 6% in men and women, respectively). In contrast, in DJ and SJ performance there were significant increases (3-11% and 4-8%, respectively). There were no differences in explosive strength adaptations between sexes. (Fernandez-Gonzalo et al. 2014).

When the adaptations of three 10-week training interventions of different training volumes were compared low-volume training including eccentric squats and plyometric exercises favoured explosive force adaptations (Methenitis et al. 2020). After low-volume training program CMJ height increased by 15%. Moderate and high-volume training did also enhance CMJ performance (9% and 7%, respectively), but the increases were significantly lower. RFD for all measured time-intervals (20, 80, 100, 120, 150, 200, 250 milliseconds) increased in low (16-31%) and moderate-volume (16-27%) training groups. After 10 weeks of high-volume training only RFD200 (27%) and RFD250 (23%) increased. The percentual change of RFD20-RFD120 values were significantly higher in both low-volume and moderate-volume group in comparison to high-volume group. (Methenitis et al. 2020). It can be hypothesised that the absence of significant increases in CMJ height in studies by Stasinaki et al. (2019) and Fernandez-Gonzalo et al. (2014) may be due to lack of plyometric exercises in the training programs. Another possibility is that the training volume in those studies has been so high that it has blunted some of explosive strength adaptations.

Balshaw et al. (2016) implemented a 12-week study much like the one of Tillin & Folland (2014) where the effects of isometric training including either sustained or explosive contractions on measures of explosive force were compared. Maximal strength increased after training with both explosive (17%) and sustained contraction (23%), but the increase was significantly higher after sustained contractions. Early rate of torque development (RTD) increased only after explosive training (RTD50 34%, RTD100 17%). RTD150 increased significantly both after explosive (18%) and sustained (12%) training. Differences in explosive force adaptations were discussed to be due to increased neural drive during early phase of contraction which was present only after explosive type training. When the two different training modes were compared for training volume measured as time under tension when torque was at least 65% of maximal, the training volume of explosive contraction training group corresponded to 7% of the training volume of the group of sustained contractions. (Balshaw et al. 2016). Again, low training volume and training including contractions with one's maximal velocity showed to favour explosive strength adaptations.

A 12-week power training program involving jump squats and squat jumps induced significant increases in CMJ peak power, peak velocity, concentric RFD, eccentric RFD, and jump height. It was pointed out that increased CMJ performance was observed simultaneously with changes in jumping technique. For example, the displacement during eccentric phase was bigger albeit the time spent in the phase did not differ. It was thus demonstrated that improved technique is a key variable contributing to enhanced jumping performance. (Cormie et al. 2009). The importance of jumping technique for increases in jumping performance demonstrated by Cormie et al. (2009) can be used to explain the findings of Vissing et al. (2008). The effects of 12 weeks of strength training or plyometric training on jumping performance were studied and only plyometric training led to significant increase in CMJ height (10%). It can be argued that despite of adaptations in maximal strength and muscle architecture the strength training program failed to provide sufficient training for jumping technique. Some conventional strength training programs still have succeeded in stimulating significant improvements in CMJ height. In the study by Bloomquist et al. (2013) a 12-week squat training program caused an increase of 7% in a group doing deep squats and 13% in a group doing shallow squats. Therefore, a sufficient similarity of utilized exercises with the jumping action itself seems to be important to elicit improvements in CMJ height.

In an early study by Aagaard et al. (2002) a 14-week training program of heavy strength training, where the used loads ranged between 3-10 RM, induced significant adaptations in all measured RFD variables. Besides absolute RFD values ranging from RFD30 to RFD200 also relative RFD for the first sixth of maximal strength increased. An improvement was also observed in EMG amplitude and rate of EMG rise for first 30, 50 and 100 milliseconds, which was reasoned to centrally contribute to increased RFD values. (Aagaard et al. 2002). Inconsistently, in another 14-week training intervention study only RFD250 increased (11%), and that increase was related to the increase of maximal force. Early phase RFD did not change and relative RFD even decreased. (Andersen et al. 2010). The difference in adaptations may be explained by the nearer to maximal velocity and effort of repetitions performed in the study by Aagaard et al. (2002) or the used periodization model with a separate tapering period.

Peltonen et al. (2018b) studied if the adaptations of explosive force after 20 weeks of hypertrophic training and 10 weeks of training for maximal strength followed by 10 weeks of power training differ. The time-course of adaptations was also examined as the measurements were carried every 3,5 weeks. Explosive strength was measured as peakRFD10, and the increase in it reached significance at week 7 in both hypertrophic training group (44%) and maximal strength training group (47%) with no significant difference between groups. After 7 weeks peakRFD10 increased only in the group that continued with power training (65%). (Peltonen et al. 2018b).

Interindividual differences in adaptation patterns have also been studied in relation to combined 10 weeks of maximal strength training and 10 weeks of power training (Peltonen et al. 2018a). Subjects were divided into three distinct groups based on how they adapted to the two 10-week training periods. First group improved peakRFD10 by 100% during the maximal strength period and by 103% during power training period compared to initial level. For the second group the values were 11% and 53%. In the last group peakRFD10 first decreased by 17% after maximal strength training and remained unchanged during power training period. (Peltonen et al. 2018a), Thus, it was demonstrated that the subjects responded to training interventions in three different ways either by improving mainly in response to maximal strength training or power training period or by not significantly improving at all after training. The differences in individual adaptation patterns may hypothetically be one reason to somewhat contradictory results regarding RFD adaptations after relatively similar training interventions seen in previous studies.

## 3.2 Adaptations to detraining

Besides studying explosive strength adaptations following different forms of strength training studies have also examined how training cessation affects different performance related variables. Andersen et al. (2005) studied the effects of 3 months detraining period on the adaptations induced by 3 months of periodized hypertrophic and heavy strength training. The detraining period of 3 months was sufficient to cause a decrease of isokinetic strength and power measured from contractions of slow and moderate velocities to levels corresponding the pre-training values. Also, muscle activation measured as EMG returned to its initial values. On the contrary, angular velocity, acceleration, total moment of force, power and peak velocity measured from maximal unloaded knee extension and RFD defined from electrically evoked twitch increased after the detraining period. (Andersen et al. 2005). Thus, it can be concluded that a relatively long detraining period may favour both voluntary explosive strength and muscles intrinsic properties related to fast force production.

More studies have examined the effects of detraining in trained populations. Branquinho et al. (2020) reported that 4 weeks of detraining after 8 weeks of low volume high intensity plyometric training caused a decrease in jumping performance in junior soccer players. However, the jump height after the detraining still exceeded the pretraining level. It should be still noted that the study took place during season, so subjects participated in four sport specific practices and one match during each intervention week including the detraining period. (Branquinho et al. 2020) In another study for adolescent athletes the effects of 12-week strength training intervention and following 3-week detraining period was examined (Gavanda et al.

2020). CMJ height increased in response to training and was unaltered after three weeks of training cessation at a group level. Interestingly, when alterations in CMJ height in response to training and detraining of individual subjects were analysed it was observed that large improvements after training were correlated (r=0.6292) with more significant decreases in response to detraining. (Gavanda et al. 2020). When the results of studies by Branquinho et al. (2020) and Gavanda et al. (2020) are compared it can be hypothesised that resistance training causes more permanent adaptations in jumping performance compared to plyometric training. Still, it needs to be noted that the relation between the duration of training and detraining somewhat differed.

In a study examining the effects of 8 weeks of combined aerobic exercising and resistance training of three different intensities followed by 4 weeks of detraining it was shown that regardless of resistance training intensity the performance level decreased to a level significantly not different from pre-training values. There were no differences between training groups of different training intensities in increases of CMJ height (11.6–13.9%) in response to total of 14 training sessions during training period. There neither was a difference between groups after detraining. However, the group that had trained with lowest relative intensity (40-55% of 1RM) was the only group that experienced a significant decrease in CMJ height. (Sousa et al. 2018) Therefore, the intensity of strength training potentially has a slight influence on the effects of subsequent detraining period on explosive tasks.

# 4 MUSCLE ARCHITECTURE

The term muscle architecture is commonly used to describe different features of a muscle including fascicle length (FL), pennation angle (PA), muscle length and muscle thickness (MT) (Blazevich 2006a). Muscles do vary in their architecture, and for example quadriceps femoris muscles seem to be different in architecture and thus it can be hypothesised that they serve somewhat different functions in human locomotion (Blazevich 2006b). Additionally, within a single muscle the architecture may vary along its length. For example, in the biceps femoris MT has been found to be higher, FL to be longer, and PA to be higher at the muscle belly in comparison to distal parts (Franchi et al. 2020).

High PA of a muscle is thought to be linked with the capacity to produce high forces. Another typical feature of highly pennated muscles is that they tend to produce force over a relatively short range of motion. The mechanisms that contribute to high force production of muscles with increased fascicle angulation are for instance greater physiological cross-sectional area (CSA) and ability of fibres to function at more optimal lengths. Low PA in turn is typical for muscles involved in movements of higher velocity and where significant length changes occur. PA and FL of a certain muscle tend to negatively correlate. (Blazevich 2006a) Additionally, the increase of PA appears to be higher in response to concentric versus eccentric training (30% vs. 5%) while FL tends to increase more after eccentric in comparison to concentric training (12% vs. 5%) when the effects of 10-week strength training interventions were compared (Franchi et al. 2014).

High contraction velocity of long fascicles has been traditionally thought to be enabled by high number of sarcomeres arranged in series (Blazevich 2006a) but a recent study by Pincheira et al. (2022) shows that at least early increases in FL are largely a consequence of increased mean sarcomere length. In fact, after short-term strength training intervention there were no significant changes in number of sarcomeres seen in neither medial nor distal part of muscle. (Pincheira et al. 2022)

## 4.1 Measuring muscle architecture

Muscle architecture in vivo is commonly measured with ultrasound (Tillin et al. 2012, Coratella et al. 2020, Ruiz-Gardenaz et al. 2018, Erskine et al. 2014). The ability of ultrasound technique to be used as a research method when examining human tissues is based on echo pulses that are emitted from a transducer and that are reflected to a transducer to different extent by different tissues like muscle and bone. The level of reflection of a certain tissue is called reflection coefficient and it is related to the water content of tissue. (Franchi et al. 2018)

Ultrasound can be used to reliably measure different variables of muscle architecture. It is still notable that certain aspects regarding the measurement conditions have an influence on reliability. Chiaramonte et el. (2019) found that intra-observer reliability for MT, CSA, and PA was 0,97, 0,92, and 0,95, respectively. Inter-observer values for MT, CSA, and PA were 0,92, 0,78, and 0,86, respectively. Even there was a trend toward lower inter-observer reliability, the difference was non-significant. (Chiaramonte et al. 2019). One important aspect influencing the reliability of ultrasound imaging is the alignment of the transducer (Franchi et al. 2018).

It should be noted that there are multiple distinct ultrasound imaging techniques that can be utilized in measuring muscle architecture. The techniques are brightness mode (B-mode) ultrasound, extended-field-of-view (EFOV) ultrasound, and 3-D ultrasound, of which the B-mode ultrasound is the most frequently used. B-mode ultrasound is optimally used to measure muscle architectural properties, FL and PA, as well as a simple variable describing muscle size, MT. The advantage of EFOV ultrasound technique is whole muscle level imaging, and it can be used to capture both transverse and longitudinal scans. The variables that EFOV is used for are muscle CSA and longitudinal muscle architecture. Devices employing EFOV ultrasound imaging technique rely on algorithms that construct an integrated image of distinct scans taken while transducer is moved along skin surface. 3-D ultrasound technique can be used to measure muscle volume, muscle belly length and 3-D muscle fascicle architecture. (Franchi et al. 2018).

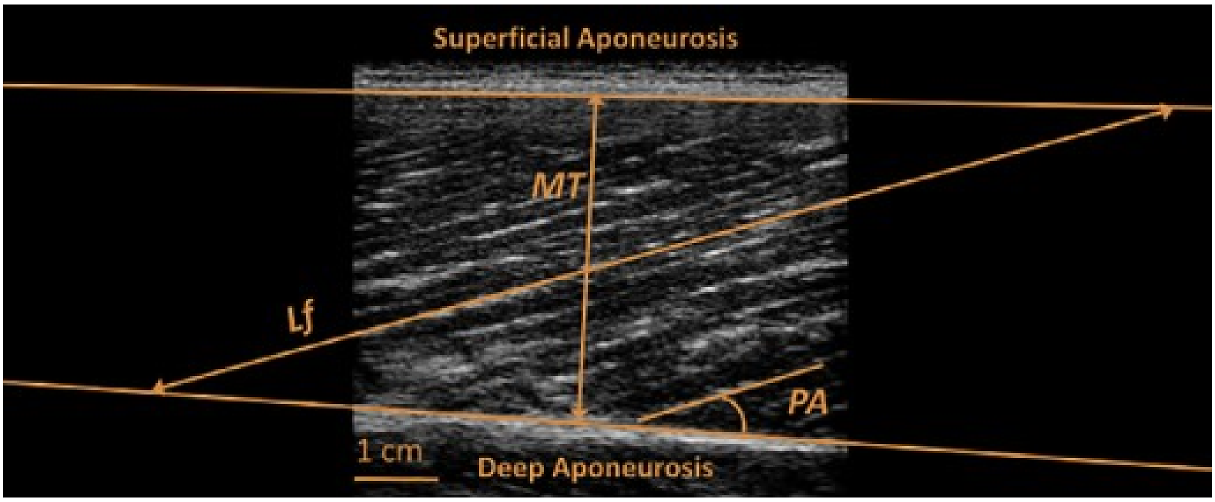

FIGURE 2. Muscle thickness, fascicle length, and pennation angle. (Franchi et al. 2018) MT, muscle thickness; Lf, fascicle length; PA, pennation angle.

Figure 2 demonstrates how essential muscle architecture variables are measured from B-mode ultrasound image. MT is the perpendicular distance between deep and superficial aponeuroses of the muscle in question (Franchi et al. 2018). PA is measured by defining the angle of insertion of the fascicles into the muscle's deep aponeurosis (Franchi et al. 2018). FL can be calculated from B-mode ultrasound image utilizing information about MT and PA, but it needs to be noted that in that case the value is just an estimation of fascicle length (Franchi et al. 2020). There are three recognized ways to estimate FL from 2D ultrasound image. Two of them utilize trigonometric functions (figure 3). The third method relies on manual extrapolation of fascicle length. The visible section of fascicle length in B-mode ultrasound image is linearly extrapolated to the linearly extended line corresponding the superficial aponeurosis. Of the three methods only the lower trigonometric function presented in figure 3 considers the curvature of fascicles. (Franchi et al. 2020)

a. $L_f = \sin(\gamma + 90^{\circ}) \times MT \times \sin(180^{\circ} - (\gamma + 180^{\circ} - PA))^{-1}$

b. $L_f = L + (h/\sin\beta)$

FIGURE 3. Trigonometric functions used to calculate fascicle length. Function a. (Blazevich et al. 2006b) and function b. (Finni et al. 2001). Lf, length of a fascicle; MT, averaged muscle thickness; $\gamma$, the angle between superficial and intermediate aponeurosis; PA, pennation angle; *L,* visible part of fascicle length between insertion to intermediate aponeurosis and the edge of image's field of view; h, distance between superficial aponeurosis and the end point of fascicle visible in the image; $\beta$, the angle between linearly the linearly extrapolated fascicle and the lenarly extrapolated superficial aponeurosis.

The reliability of muscle architecture variables measured with ultrasound has been shown to be good. Tillin et al. (2012) reported the ICC to be 0.93 for MT, 0.92 for FL, and 0.92 for PA when measured from vastus lateralis muscle (VL) with B-mode ultrasound. However, in recent study by Franchi et al. (2020) the reliability and absolute values of FL measured with B-mode and EFOV ultrasounds were compared. The intrasession reliability was good when measured with EFOV (ICC = 0.91-0.98) as well as when fascicle length was extrapolated from B-mode ultrasound image either manually or based on trigonometric functions presented in figure 3 (0.96-0.99). The extrapolation methods had a tendency to overestimate the FL in comparison to EFOV (0.33-1.91 cm). However, for some subjects the extrapolation methods also underestimated FL. In conclusion, despite the high intraclass correlation the systematic error seems not to be constant between subjects. Thus, EFOV is recommended to be used to accurately measure FL. Still, it was recognized that as muscles differ in their thickness, PA, and fascicle and aponeurosis orientation the usefulness of extrapolation methods also varies across muscles. (Franchi et al. 2020)

Also, 3D-ultrasound can be used to measure FL. Pincheira et al. (2022) utilized a method where the whole muscle was imaged with 3D-ultrasound and fascicle was digitized with 6 points to allow considering the curvature of a fascicle. The length of multiple fascicles was analysed to calculate average length of fascicle at certain site of muscle. It was reported that the measurement error of the described method was negligible and thus the inter-day variability of FL was low. (Pincheira et al. 2022)

Noorkoiv et al. (2010) examined intra-day reliability as well as intra- and inter-experimenter reliability of CSA (figure 4) of quadriceps muscles at different sections of muscles. ICC for inter-day reliability was 0.92-0.99. Intra- and inter-experimenter reliability was expressed as coefficient of variation (CV) and values ranged between 0.6 and 2.7%. (Noorkoiv et al. 2010)

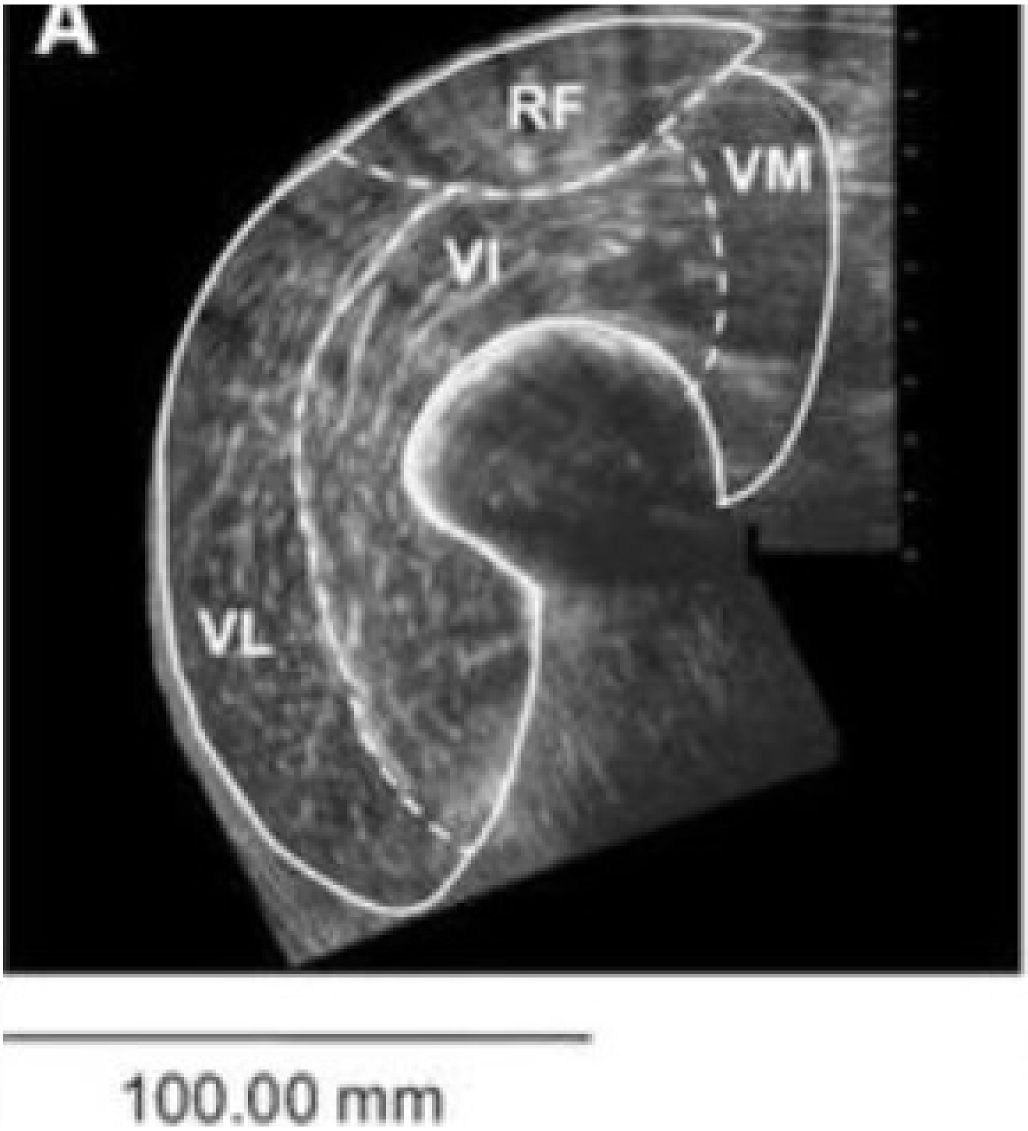

FIGURE 4. Muscle cross-sectional area. (Noorkoiv et al. 2010)

# 5 MORPHOLOGICAL ADAPTATIONS TO STRENGTH TRAINING AND DETRAINING

The effects of various strength training interventions on muscle architecture in previously untrained subjects will be reviewed next. Attention will be paid on the time needed to stimulate significant changes in each of the variables describing muscle architecture (Table 2). Once again, previous studies are gone through in order based on the length of training intervention. After that, the effects of detraining on muscle architecture adaptations will be discussed.

## 5.1 Adaptations to training

Significant changes in FL have been seen in response to already 3 weeks of eccentric training (Pinchiera et al. 2022). FL was measured both at medial and distal sites of a muscle and increase of FL (21%) was present only in the distal parts of muscle. As 3D ultrasound measurement of muscle architecture was accompanied with microendoscopy measurement of sarcomere level changes it was possible to show that increased FL was mainly due to increased mean length of sarcomeres (17%) and not to higher number of sarcomeres in series (no significant changes observed). (Pincheira et al. 2022) Therefore, it seems that early morphological adaptations may be heterogenous across the different sections of a muscle. Thus, a measurement site potentially affects the found adaptations. A 4-week isometric training intervention was sufficient to elicit significant increase (7%) in VL MT. However, in FL and PA there weren't any changes. (Tillin et al. 2012) Partly inconsistently, a 5-week isokinetic concentric-eccentric training for lower extremities including 12 training session in total did not stimulate any significant morphological adaptation when MT, FL, and PA were measured (Blazevich et al. 2007b).

On the contrary, 5 weeks of either concentric or eccentric isokinetic training for 15 sessions in total did both result in significant changes in muscle architecture of VL (Blazevich et al. 2007a). FL increased by 6.3% after concentric and by 3.1% after eccentric training. PA increased by 11.1% after concentric and by 11.5% after eccentric training. Also, MT increased significantly in response to 5 weeks of training. Interestingly, 5 additional training weeks elicited significant improvements only in PA (concentric 13.3%, eccentric 21,4%) while FL and MT did not increase significantly on training weeks 6–10. (Blazevich et al. 2007a) It can be concluded that even short training interventions of 4–5 weeks have a potential to elicit significant changes in various muscle architecture variables. Both isometric and dynamic training may significantly affect muscle architecture if the number of training sessions in total is high enough. The effect of training either to failure or not to failure has also been examined, and the increases in PA, FL and CSA were found to be significant from baseline but similar to each other (Santanielo et al. 2020).

TABLE 2. Minimum time needed for a range of morphological adaptations of vastus lateralis.

| Muscle architecture variable | Weeks of training needed to elicit significant adaptations/sessions in total | Training modality | Percent change | Study |
|---|---|---|---|---|
| Muscle thickness | 4 weeks / 16 sessions | Isometric | 7% | Tillin et al. 2012 |
| Pennation angle | 5 weeks / 15 sessions | Isokinetic eccentric | 11.5% | Blazevich et al. 2007a |
| Fascicle length | 3 weeks / 9 sessions | Eccentric | 21% | Pinchiera et al. 2022 |
| Cross-sectional area | 4 weeks / 12 sessions | Concentric-eccentric | 16.3% | Boone et al. 2015 |

Besides muscle architecture also muscle size affects muscle's functional properties. Erskine et al. (2014) showed that training-induced muscle hypertrophy highly correlated with adaptations in both isometric and dynamic force and thus largely explained the interindividual differences in performance after a training intervention.  In a study by DeFreitas et al. (2011) an 8-week training intervention specially designed to stimulate hypertrophy in quadriceps muscles was implemented by previously untrained subjects and the adaptations in muscle size were assessed weekly. Summed CSA of quadriceps muscles was measured with computed tomography. There was a significant increase in CSA between each of the training weeks starting already from week 1. Even the measurement method couldn't distinguish between muscle tissue and intramuscular fluid it was reasoned based on high reported perceived muscle soreness by subjects on weeks 1 and 2 that the increases seen on CSA were largely due to muscle oedema during those weeks. Still, researchers reasoned that as the muscle soreness ceased on week 3 and as the CSA measured on week 3 significantly differed from the CSA on week 1 when the swelling was hypothesised to be highest, significant hypertrophy occurred latest at third training week. The total increase in quadriceps CSA in response to 8 weeks of high intensity resistance training three times a week was 9.6%. (DeFreitas et al. 2011)

It should be noted that different quadricep muscles appear to adapt differently to strength training what comes to hypertrophy. Zaras et al. (2021) reported that 7 weeks of conventional high-intensity strength training caused an increase of 12.5% in total quadriceps CSA. However, when the adaptations of single muscles were viewed it was noted that the CSA of VL, VI and VM had increased (16.7%, 12.1%, and 19.7%, respectively) while for RF there weren't any significant changes. (Zaras et al. 2021) Similar increases in VL CSA have been reported by Sterczala et al. (2020). Previously untrained subjects participated in 8-week lower-body resistance training program thrice a week which stimulated VL CSA to increase by 18.7%. (Sterczala et al. 2020)

Boone et al. (2015) aimed to investigate the effects of short-term strength training on muscle hypertrophy of VL. They reported that 4 weeks of lower body strength training 3 times a week was sufficient to elicit an increase of 16.3% in VL CSA. Thus, it can be concluded that VL hypertrophy can occur in relatively short period of time when the training stimulus is intense enough. The possibility to affect muscle size with other training modes than resistance training has also been examined. Vissing et al. (2008) compared the effects of 12 weeks of either conventional strength training or plyometric training on muscle architecture. Both training modes caused a significant increase in CSA of VL. Strength training induced an increase of 8.4% and plyometric training of 7.5%. (Vissing et al. 2008) Thus, it seems that also other training modes than resistance training with external loads are effective in stimulating increases in muscle size.

Stasinaki et al. (2019) have studied the effect of contraction velocity on morphological adaptations. Six weeks of either slow or fast eccentric only training induced somewhat different changes in muscle architecture. VL MT increased only in response to slow training (6%). PA changed after neither of the training programs. VL FL increased significantly after fast training (10.0%) but not after slow training. (Stasinaki et al. 2019) In conclusion, besides contraction type the contraction velocity can potentially affect the morphological adaptations. However, not all studies have reported the contraction velocity to correlate with FL adaptations. Marzilger et al. (2020) reported that FL adaptations to 11 weeks of eccentric training (average 5.2%) were independent of lengthening velocity used in training. The inconsistency of the results can potentially be due to load selection. In the study by Stasinaki et al. (2019) fast training group trained with lower (70%) relative load than slow training group (90%) whereas in the study by Marzilger et al. (2020) the relative load (100%) was same for all training groups. Thus, it seems to be favourable to train with submaximal load to enhance adaptations of FL in response to training with fast contraction velocities.

Ikezoe et al. (2020) have in turn compared the effects of high load low reps (HLLR) and low load high reps (LLHR) training in muscle architecture. In response to training thrice per week for eight weeks MT of rectus femoris muscle increased by 20,4% after HLLR training and by 11,3% after LLHR training with no significant difference between groups. The time-course of adaptations was similar as the significance of adaptations was first present at week 4 in both training groups. (Ikezoe et al. 2020)

Possible differences in the morphological adaptations in response to strength training between men and women have also been studied. An 8-week eccentric only training intervention including exercises with supramaximal load showed that morphological adaptations are not sex-related despite PA. VL MT increased similarly in men and women (11% and 13%, respectively), as did VL FL too (12% and 7%, respectively). PA increased significantly only in women (14%) but not in men (5%). (Coratella et al. 2018) Therefore, possible sex differences in adaptation patterns should be taken into consideration when interpreting the results of studies where subjects are both men and women.

Concentric and eccentric strength training affect muscle architecture differentially. PA was significantly greater influenced by concentric training while FL increased significantly more in response to eccentric training (Franchi et al. 2014). Interestingly, the two different training modes caused also heterogenous muscle volume adaptations along the length of the muscle. Distal muscle volume growth was higher in response to eccentric training while concentric training preferred increases in muscle volume measured at medial site of the muscle. (Franchi et al. 2014) Therefore, it seems to be important to be aware of somewhat distinct adaptations eccentric and concentric training cause when comparing the results of studies that have used diverse training interventions. The non-uniform adaptations of muscle size to strength training were also demonstrated by Bloomquist et al. (2013) who reported that the increases of quadriceps cross-sectional area after 12 weeks of strength training varied between 4 and 7% at different sites of muscle's length. Besides the notion that the muscle architecture adaptations may be heterogenous longitudinally at different sites of a muscle, it has been shown that the adaptations may significantly differ cross-sectionally at different sites of a muscle. Wells et al. (2014) measured morphological adaptations of VL to 15 weeks of strength training at two different sites. The measurement points were the point mid-way between the greater trochanter and lateral epicondyle of the femur and a point 5 cm more medial from that. MT increased significantly more at the more medial site of VL. Additionally, only the muscle architecture measures from more medial site correlated with performance adaptations (Wells et al. 2014). Thus, the somewhat controversial results regarding the muscle architecture adaptations and their connections to explosive strength may be also partly explained by differing measurement sites across studies.

Longer training intervention studies with multiple measurement points have an ability to characterize time-course of training-induced adaptations. Baroni et al. (2013) studied the time-course of adaptations in muscle size during a 12-week eccentric isokinetic training program. Muscle size of lower extremities was measured as CSA of rectus femoris (RF) and as summed MT of VL, vastus medialis (VM), and RF. Both CSA and summed MT increased significantly from baseline for week 4 (8,8% and 6.1%, respectively) and from week 4 to week 8 (16,9% and 9,3%, respectively). Neither CSA nor summed MT continued to increase significantly after week 8. (Baroni et al. 2013) In the study by Kubo et al. (2010) the increase of quadriceps CSA achieved significance only after 12 weeks of training and was markedly lower (5.5%) than reported by Baroni et al. (2013). The difference in the time-course and magnitude of adaptations may be due to differences in training intervention. Kubo et al. (2010) employed long (15 sec) sub-maximal isometric contractions in their training program, which may have compromised the adaptations of muscle size. However, based on the findings by Baroni et al. (2013) it may be beneficial, or even necessary, to modify training program after 2 months to further elicit significant adaptations in muscle size.

## 5.2 Adaptations to detraining

Most studies examining the effects of detraining following a training period have typically used relatively long periods of training cessation. Interestingly, distinct muscle architecture variables potentially response to detraining differently. Blazevich et al. (2007a) reported that 3 months of detraining after initial 10-week training period resulted in non-significant increase of FL, decrease of PA to the level corresponding to baseline value, and non-significant decrease of MT. However, the decrease of MT was sizeable enough that post-detraining values no longer significantly differed from pre-training values. (Blazevich et al. 2007a)

Kubo et al. (2010) have reported that only one month of detraining after initial 12-week training period may be sufficient to decrease quadriceps CSA to the level not significantly different from pre-training values. Interestingly, as various muscle-tendon unit properties were studied it was demonstrated that variables adapting faster during training were better maintained during detraining when in turn slower adapted variables decreased faster once detraining period started. (Kubo et al. 2010) In adolescent athletes a 3-week detraining after 12-week resistance training period was insufficient to cause any changes in RF and VL MT, and thus the values also remained above the pre-training level (Gavanda et al. 2020).

Beside morphological adaptations detraining potentially affects muscle fibre composition. Andersen et al. (2005) reported a significant increase in type IIx myosin heavy chains and total type II myosin heavy chain proportion during 12-week detraining period which was carried out after 12 weeks of training. Thus, it can be concluded that adaptations to detraining may promote ability for fast force production. The effects of shorter detraining periods should be also studied in future.

# 6 MUSCLE ARCHITECTURE AND EXPLOSIVE STRENGTH

The importance of different muscle architectural variables for explosive actions has been studied by comparing the muscle morphology of athletes of different sports, athletes of different performance levels and athletes to non-trained controls. Sprint runners and especially high-level sprinters have been found to have low pennation angle and relatively long fascicles. Highly pennated muscles seem to be favoured in endurance performances as shorter fascicles seem to be more cost-effective. (Blazevich et al. 2006a) More recent cross-sectional studies have examined the relations between muscle architecture and explosive strength in more homogenous populations. Studies describing those associations regarding lower extremities are reviewed below and significant correlations are summarized in table 3.

TABLE 3. Observed significant correlations between explosive strength and muscle architecture.

| Explosive strength variable | Muscle architecture variable | Correlation | Study design | Study |
|---|---|---|---|---|
| CMJ peak force | VL MT | 0.67 | Cross-sectional | Secomb et al. 2015 |
| CMJ peak force | VL PA | 0.54 | Cross-sectional | Secomb et al. 2015 |
| Late phase RFD | VI MT | 0.54-0.69 | Cross-sectional | Coratella et al. 2020 |
| Late phase RFD | VL FL | 0.53-0.62 | Cross-sectional | Coratella et al. 2020 |
| Late phase RFD | VI FL | 0.57-0.64 | Cross-sectional | Coratella et al. 2020 |
| Late phase RFD | VL FL | 0.60-0.68 | Longitudinal | Zaras et al. 2016 |
| Late phase RFD | VL MT | 0.64-0.87 | Longitudinal | Zaras et al. 2016 |
| Early and late phase RFD | VL FL | 0.60-0.68 | Longitudinal | Stasinaki et al. 2019 |
| Early and late phase RFD | VL MT | 0.64-0.87 | Longitudinal | Stasinaki et al. 2019 |

CMJ, countermovement jump; VL, vastus lateralis; MT, muscle thickness; PA, pennation angle; RFD, rate of force development; VI, vastus intermedius; FL, fascicle length.

The literature describing correlations between muscle architecture and isometrically measured explosive strength in cross-sectional settings appears to be somewhat limited. In recreationally resistance-trained subjects vastus intermedius muscle (VI) FL and MT as well as VL FL were found to correlate with late phase RFD values (r=0.570-0.643, r=0.694-0.546, and r=0.535-629, respectively). PA did not correlate with any RFD variables. (Coratella et al. 2020). However, significant but weak correlations between PA and late phase RFD as well as muscle volume and late phase RFD have been reported elsewhere (Maden-Wilkinson et al. 2021). Still, the relationship between late phase RFD and muscle size was hypothesised to likely be due to known association between late phase RFD and maximal force along with connection between maximal force and muscle size (Maden-Wilkinson et al. 2021). More studies have studied correlations between muscle architecture and dynamic explosive performance. When studied in young athletes, significant correlations were found between VL MT and CMJ peak force (r=0.67) and VL PA and CMJ peak force (r=0.54). No significant correlations were reported for FL or CMJ height with any of the other variables. (Secomb et al. 2015).

Earp et al. (2010) studied correlations between leg muscles' architecture and CMJ, SJ and drop jump (DJ) performance in subjects familiar with either speed, plyometric or power training. None of the VL muscle architecture measures correlated with performance in vertical jump tests. In contrast, PA of lateral gastrocnemius (LG) muscle predicted jump height and relative power in all jumps and LG MT predicted absolute peak power in all jumps. (Earp et al. 2010). In a later study with subjects similarly familiar with training involving fast force production PA of both VL and LG found to predict early RFD during DJ. Therefore, it was reasoned that high pennation angle of leg muscles may contribute to enhanced ability to handle high eccentric forces experienced for example in drop jump. (Earp et al. 2011). However, in a meta-analysis of correlations between muscle architecture and jumping performance it was shown that VL thickness was related to CMJ height. The meta-analysis did not reveal any other significant correlations between muscle architecture of lower extremities and vertical jump performance. (Ruiz-Gardenaz et al. 2018). It is still notable that the meta-analysis only included 6 studies.

Recently the studies regarding relations between muscle architecture and explosive strength have employed longitudinal design to detect possible causal connections between morphological adaptations of different muscles and improvements in explosive tasks. Studies describing connections between changes in morphological adaptations and changes in explosive strength after training interventions of different lengths are reviewed next, again in order form shortest to longest training periods. However, the amount of such studies in untrained adult population is limited, and more studies have focused on the relations between explosive strength and muscle fibre composition.

A 6-week training period of eccentric only training induced an increase in both VL FL and RFD measured from isometric knee-extension (Stasinaki et al. 2019). The percentual change of VL FL was found to correlate with percentual change of RFD variables ranging from RFD30 to RFD200 at knee angles of 90º and 120º (r=0.506-0.618). (Stasinaki et al. 2019) There are also studies where no correlations between muscle architecture and explosive strength adaptations have been detected. In a study examining the effects of 12 weeks squatting program significant adaptations were found in CMJ height, PA, and CSA, but still no correlations between muscle morphology and performance weren't present (Bloomquist et al. 2013).

Methenitis et al. (2020) studied the effects of combined conventional strength training and plyometric training at three different volumes on explosive strength and muscle fibre type composition. It was found out that both change in dynamic explosive strength measured as CMJ height and change in isometric explosive strength measured as early RFD correlated with change in type IIx muscle fibres. Large increase in explosive strength was related to small reduction in type IIx muscle fibres. (Methenitis et al. 2020) The importance of type IIx muscle fibres especially for early explosive force production after strength training intervention was demonstrated also in the study by Andersen et al. (2010) where decrease in early relative RFD after conventional strength training correlated with the reduction of type IIx muscle fibre percentual area. In consideration of the results of above reviewed studies, it appears to be necessary to be aware of possible effects of muscle fibre composition change on explosive strength also when it is not measured and the adaptations are being explained by different variables, for example muscle architecture. Type IIx muscle fibre proportion seems to decrease after both conventional strength training (Andersen et al. 2010) and combined power and plyometric training (Methenitis et al. 2020) but low volume of training may attenuate the reduction and thus be favourable for explosive strength adaptations.

The connections between muscle architecture and explosive strength adaptations have also been studied in more trained populations. A 10-week combined sport specific, strength, weightlifting, and assistance training caused significant improvements various explosive actions and muscle architecture. After training RFD100, RFD150, RFD200, and RFD250 correlated with VL FL (0.601-0.683) and VL MT (0.645-0.875). FL was found to correlate also with shotput performance and hang power clean. (Zaras et a. 2016) VL FL appears to be a muscle architecture variable which improvement as a result of training is related to enhanced isometric explosive strength and to some extent also to dynamic explosive type actions. However, the literature regarding the topic is limited and thus, more studies are needed. Especially, the connection between morphological adaptations and less complex dynamic explosive tasks, like vertical jumps, need to be examined in the future.

# 7 RESEARCH QUESTIONS AND HYPOTHESES

The purposes of this study are to characterize the time-course of explosive strength and morphological adaptations, to examine if explosive strength adaptations correlate with changes in muscle architecture, and to explore how detraining period affects the adaptations.

**RQ 1:** Do adaptations of isometric explosive strength reach significance during the 7-week combined resistance and plyometric training?

**H 1: Yes.** Variety of RFD variables has been shown to increase significantly (12-15%) in response to training interventions lasting 4 (Tillin et al. 2012) to 6 weeks (Stasinaki et al. 2019) in untrained subjects.

**RQ 2:** Do adaptations of dynamic explosive strength reach significance during the 7-week combined resistance and plyometric training?

**H 2: Yes.** Combined resistance and plyometric training for 10 weeks has been shown to induce significant (15%) increases in CMJ height (Methenitis et al. 2020). However, the effects of shorter periods of combined training have not been studied before in untrained subjects.

**RQ 3:** Do adaptations of muscle architecture reach significance during the 7-week combined resistance and plyometric training?

**H 3: Yes.** Both muscle thickness (Tillin et al. 2012), pennation angle (Blazevich et al. 2007a), fascicle length (Blazevich et al. 2007a), and cross-sectional area (Boone et al. 2015) have been shown to significantly increase in response to 4-5 weeks of strength training. The specific effects of combined resistance and plyometric training on variety of muscle architecture variables have not been studied before in untrained subjects.

**RQ 4:** Are explosive strength adaptations connected to morphological adaptations?

**H 4: Yes.** Percentual change in vastus lateralis fascicle length has been shown to correlate with percentual change of isometric explosive strength after a strength training intervention of moderate length (Stasinaki et al. 2019). In cross-sectional studies pennation angle (Earp et al. 2011) and muscle thickness (Fernandez-Gonzalo et al. 2014) have been shown to correlate with jumping performance.

**RQ 5:** Does explosive strength significantly decrease during 5 weeks of detraining?

**H 5: Yes.** Training cessation for 4 weeks have been reported to cause a significant decrease in jumping height in a trained population (Branquinho et al. 2020). The effects of short-term training cessation on jump height or fast isometric force production has not been studied in untrained subjects.

**RQ 6:** Are there changes in muscle architecture during 5 weeks of detraining?

**H 6: Yes.** One month of detraining has been shown to significantly decrease muscle CSA (Kubo et al. 2010). It can be assumed that muscle architecture variables might response differently to detraining as three months of training cessation caused a significant increase only in pennation angle while fascicle length non-significantly increased and muscle thickness non-significantly decreased (Blazevich et al. 2007a).

# 8 METHODS

This thesis was conducted as a part of larger project where data was collected for multiple theses. The project was led by Dr. Ahtiainen. A general study design and the specific methods used to collect data for this thesis are presented below. The study design was approved by the local ethics committee.

## 8.1 Subjects

There were 17 healthy and previously untrained subjects participating in the study, however 3 of the subjects were not able to finish the study due to health reasons. The subjects had not participated in systematic strength training in the last 6 months. Participation to competitive sport and regular strenuous endurance exercising were also regarded as exclusion criteria. There were 10 male and 7 female subjects. The mean age of subjects was 28±5 years. Subjects were informed about the risks of the study and the voluntariness of participation.

## 8.2 Study design

The study consisted of a 7-week strength training intervention which was followed by a 5-week detraining period (figure 5). Before intervention subjects participated to one familiarization session where the study design was carefully explained to subjects and the measurements were gone through to minimize the effect of learning on results between control and pre-measurements. Control measurements took place 2 weeks before pre-measurements and the initiation of training intervention. The measurements were repeated after 3,5 weeks of training, after 7 weeks of training, and after the 5-week detraining period. The measurements included ultrasound measurement of VL, body composition assessment with bioimpedance, and testing of isometric and dynamic explosive strength. Dynamic explosive strength was additionally monitored on each training week through the intervention.

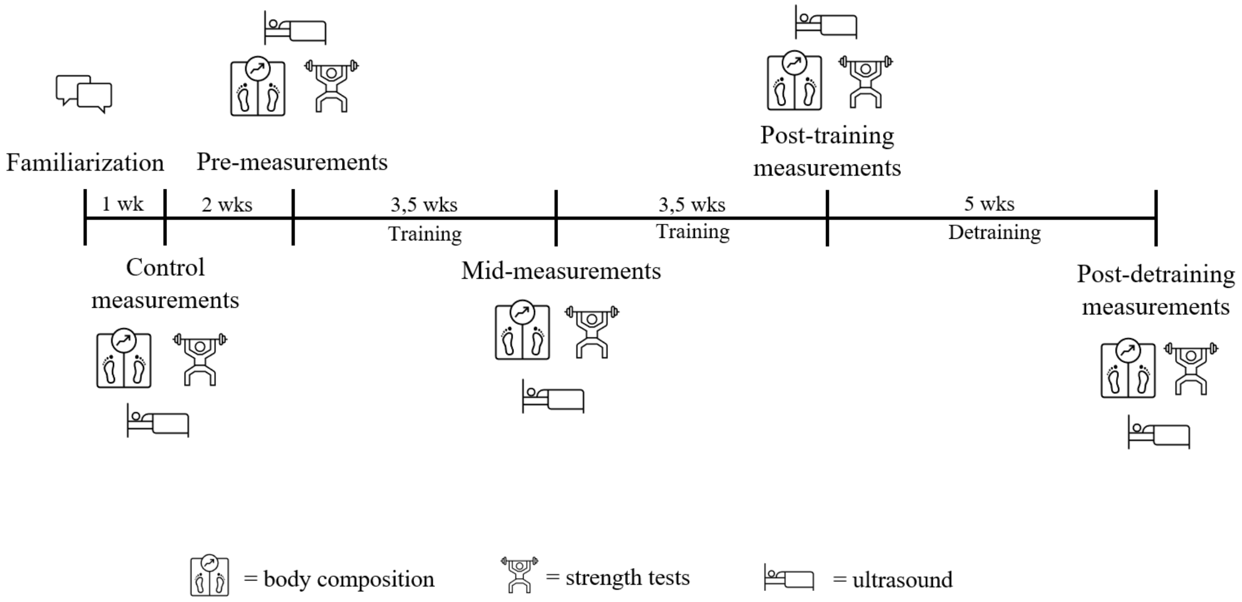

FIGURE 5. Study design.

### 8.3 Strength training

The 7-week training intervention included 13 training sessions in total, and subjects were required to complete at least 12 of the sessions to be included in final analyses. The training sessions were separated by 48 hours. The strength training sessions took place at the same time of the day (morning/noon/evening) for each subject. The training program consisted of low volume of plyometric exercises combined with conventional strength training for both lower and upper body. Each training session began with 5 minutes of cycling at self-determined tempo. After cycling subjects completed dynamic stretching and activation movements, which were squat, lunge, walking from standing forward bend to plank position and back, high knees with calf raise, and side squat. After warm-up subjects performed 5 maximal CMJs. Strength training program included leg press, knee-extension, bench press, bicep curl, and chest-supported seated row. Three sets were performed in leg press, bench press, and chest-supported seated row and five sets in knee-extension and bicep curl. The concentric phase of each repetition was executed as fast as possible whereas the eccentric phase was instructed to last 2 seconds without pause between the two phases of the movement. Rest period between the sets was 2 minutes. The loads for exercises were defined in the beginning of the intervention based on 1RM (knee-extension and biceps curl) or 3-5RM (leg press, bench press, and chest-supported seated row) test results and they were modified every week. The loads were defined to allow sets of 8-10 repetitions and leaving 2-3 repetitions in reserve. On the second session of each training week the last set of each exercise was done to concentric failure to get the idea of real capacity of a subject. Training loads were modified based on number of repetitions in the failure set (table 4). Strength training sessions were monitored by research staff to ensure proper technique and correct tempo for each repetition.

TABLE 4. Formula for load modification during the strength training.

| Repetitions | Leg press | Knee extension | Bench press | Bicep curl | Chest supported row |
|---|---|---|---|---|---|
| < 5 | -7.5 kg | -7.5 kg | -5 kg | -2.5 kg | -2.5 kg |
| 6-7 | -5 kg | -5 kg | -2.5 kg | -1 kg | -1.25 kg |
| 8-10 | 0 | 0 | 0 | 0 | 0 |
| 11-12 | +2.5 kg | +2.5 kg | +2.5 kg | +1 kg | +1.25 kg |
| 13-15 | +5 kg | +5 kg | +5 kg | +2.5 kg | +2.5 kg |
| 16-20 | +7.5 kg | +7.5 kg | +7.5 kg | +3.5 kg | +5 kg |
| 20 > | +10 kg | +10 kg | +10 kg | +5 kg | +7.5 kg |

### 8.4 Detraining

The detraining period lasted for 5 weeks. The subjects were carefully instructed how to independently implement the detraining period. All kind of strength, speed, and bodyweight training was forbidden. Also, high intensity training was not allowed. Subjects were told not to increase the volume of low intensity aerobic exercise or recreational games and other sports. Generally, they were guided to maintain their normal physical activity.

## 8.5 Measurements

Subjects were guided to follow a set of instructions before attending the measurements at the laboratory. Drinking of coffee and other drinks including caffeine, drinking of alcohol, and smoking or use of snuff were denied for 12 hours before measurements. Subjects were also told not to implement any strenuous exercise for 48 hours preceding measurements. Finally, subjects were asked to drink 500 ml of water for 1 hour before measurements to standardize the state of hydration.

***Body composition.*** Body composition of subjects was measured with InBody 770 device (InBody Co., Ltd, Korea) which relies on bioimpedance technique. Weight, fat percent, and segmental muscle mass were tracked along the study.

***Countermovement jump.*** CMJs were done on force plate to measure flight time and to further calculate jump height. Subjects were instructed to keep hands on hips during the jump. In starting position of the jump subjects stood hip width apart. Countermovement was performed from self-selected depth that the subject felt optimal. Subjects were instructed to jump as high as possible. Ground reaction force data was collected with custom-made force plate (University of Jyväskylä, Finland) which was connected via AD-converter to a computer with Signal 4.10 software (Cambridge Electronic Design Ltd., Milton, Cambridge, UK). Sampling rate was 1000 Hz. CMJ data was analysed with Signal 4.10 software (Cambridge Electronic Design Ltd., Milton, Cambridge, UK). Jump height was calculated based on flight time using the following formula ($h=gt^2/8$) (Bosco et al. 1983). The result of the best trial was utilized in further analyses.

***Unilateral knee extension.*** RFD was measured from unilateral knee extension. All subjects performed the extension with right leg. Subjects were seated on a custom-made chair. Both hip and knee angles were set to 90° with aid of a goniometer. There was a belt that was fastened around the hips to minimize the movement of the hip while maximally extending the knee. To serve the same purpose there was a strap on the level of shoulders attached to the chair. The ankle of the subject was attached to a custom-made force sensor (University of Jyväskylä, Finland) with a strap placed two centimetres above medial malleoli. The distance between lateral epicondyle of tibia and the upper edge of force sensor was measured to attain information about the length of moment arm and to be able to further calculate torque and rate of torque development. Before maximal attempts 3 warm-up contractions were performed. Subjects were instructed to contract for 3-4 seconds with force corresponding the estimated level of 50% of maximal contraction. The contractions during which force data was recorded were instructed to be performed "as fast and as hard as possible", without any countermovement, and with a duration of 1 second. Five successful trials were done with 1 minute's rest between. Trial was regarded as successful when the peak force exceeded 80% of subject's maximal voluntary contraction. Force data from isometric contractions was analysed with Spike 2 software (Cambridge Electronic Design Ltd., Milton, Cambridge, UK). RFD was calculated for a time-interval of 250 milliseconds from the beginning of the contraction with a custom-made script. The length of time-interval was chosen based on previous studies where late-phase RFD has been shown to be more reliable than early-phase RFD (Drake et al. 2019; Dos Santos et al. 2017). The script defined the beginning of the contraction to be the point where mean force for 3 upcoming milliseconds was 0.75 N more than the mean force of previous 32 milliseconds. RFD was calculated by dividing the change in force by the change in time (Maffiuletti et al. 2016). The result of the best trial out of five successful RFD trials was utilized in further analyses.

***Muscle size and architecture.*** Muscle size and architecture of VL were measured with B-mode axial plane ultrasound (model SSD-α10, Aloka, Tokyo, Japan). A 10 MHz linear-array probe (60 mm width) and NextGen LOGIQ c ultrasound console (GE Healthcare UK, Ltd., Chalfonth, Buckinghamshire, UK) were used for measurements. To enhance the reliability of ultrasound data one practiced examiner executed all ultrasound measurements. All ultrasound measurements were done for the right leg of each subject. PA and MT were measured with conventional B-mode ultrasound, while for CSA measurements extended-field-of-view was employed. Before implementing the ultrasound measurement, the subjects rested for 15 minutes in supine position to minimize the effect of fluid shift on the results. Ultrasound measurement was carried out while subject was lying supine in standardized position. There was a custom-made support placed under the knees and between the ankles. The support between ankles standardized the distance between ankles to 20 centimetres. Additionally, to avoid the rotation of limbs there was an elastic strap set around the feet (figure 6).

FIGURE 6. Custom-made supports used during the ultrasound measurements.

The measurement site was defined by measuring the mid-point between greater trochanter and the central point of patella, and an axial line was drawn there. All markings to skin were done with permanent pen, and subjects were instructed to regularly strengthen the markings to allow measurement at the same specific location. However, the sites were also verified based on anthropometric landmarks and images of the measurement sites before every measurement. While ultrasound measurements were done, the subjects were instructed to lay still and to have their muscles relaxed. To promote probe-skin contact transmission gel was abundantly applied on the skin. Excessive pressure on the muscle while measuring it was avoided to prevent any compression of muscle. During all measurements a custom-made probe support was utilized to aid with holding the probe perpendicular in relation to the muscle (figure 7).

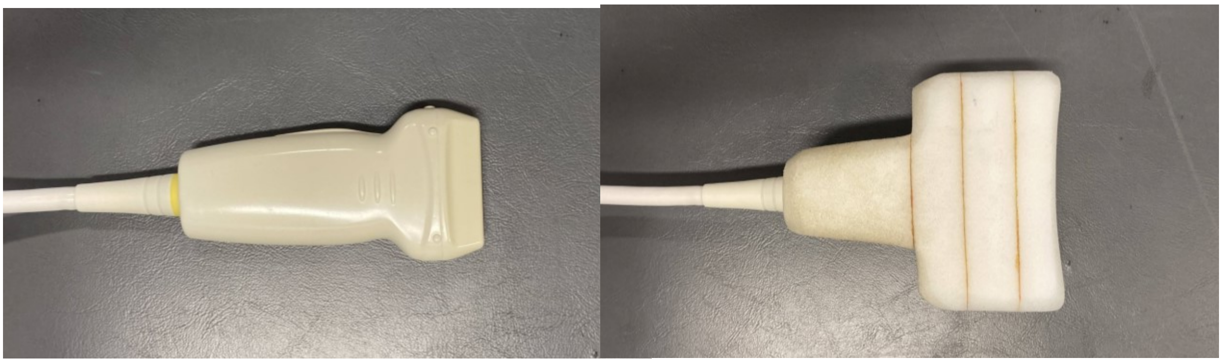

FIGURE 7. The ultrasound probe without and with the custom-made support.

CSA was measured in EFOV by manually moving the probe from lateral to medial side of thigh along the marked axial line (figure 8) with constant velocity to ensure optimal skin contact through the scan. To allow analysing of MT and PA there were scans taken also with probe placed longitudinally along the thigh. The point where MT and PA were measured was the mid-point on the line drawn between greater trochanter and the central point of patella (figure 8).

FIGURE 8. Mid-point between greater trochanter and the central point of patella (biggest black mark, the site for MT and PA measurement) and axial line (small dots) drawn at the level of mid-point (the line followed during CSA measurement).

Ultrasound data was analysed with ImageJ software (National Institutes of Health, Bethesda, Maryland, US). All analyses were performed by the same examiner who did the ultrasound measurements. The straight-line function was used to scale the pixels of images to centimetres. The polygon function was used to mark the outlines of a muscle and to further analyse muscle's CSA (figure 7). When muscle's outlines were marked the surrounding fascia was left outside of the delimited area. MT was defined with straight-line function by calculating the distance between superficial and intermediate aponeuroses. PA was measured by defining the angle of insertion of the fascicles into the muscle’s deep aponeurosis. For each variable characterizing the muscle size or architecture the mean of the two closest values was calculated and the result was used in further analyses.

## 8.6 Statistical analyses

Statistical analyses were conducted with Microsoft Excel (Microsoft Corporation, US) and IBM SPSS Statistics 26 (IBM Corporation, US) software. The normality of data was tested with Kolmogorov-Smirnov test. The reliability of each variable was checked with calculation of ICC and CV%. Repeated measures ANOVA was used to analyse if there were significant changes in any of the measured variables in response to training and detraining. When significant differences between means were seen the specific time-points were detected with Bonferroni post hoc analysis. Possible correlations between muscle architecture and explosive strength adaptations were explored with Pearson’s correlation coefficient. The significance level was set to $p<0.05$.

# 9 RESULTS

All variables were found to be reliable in means of intra-class correlation coefficient and coefficient of variation (table 5). Changes in CMJ height, RFD, VL CSA, VL MT, and VL PA in response to 7 weeks of training followed by 5 weeks of detraining are described in figures below (figures 9-13). CMJ height was significantly higher post training compared to pre-training level. Detraining period caused a non-significant decrease in CMJ height to a level that however no more differed from the pre-training level (figure 9). There were no significant changes in RFD during the intervention (figure 10).

TABLE 5. Reliability of measured variables.

| Variable | CMJ | RFD | CSA VL | MT VL | PA VL |
|---|---|---|---|---|---|
| ICC | 0.955 | 0.826 | 0.997 | 0.991 | 0.957 |
| CV% | 2.2 | 4.0 | 0.5 | 0.7 | 1.6 |

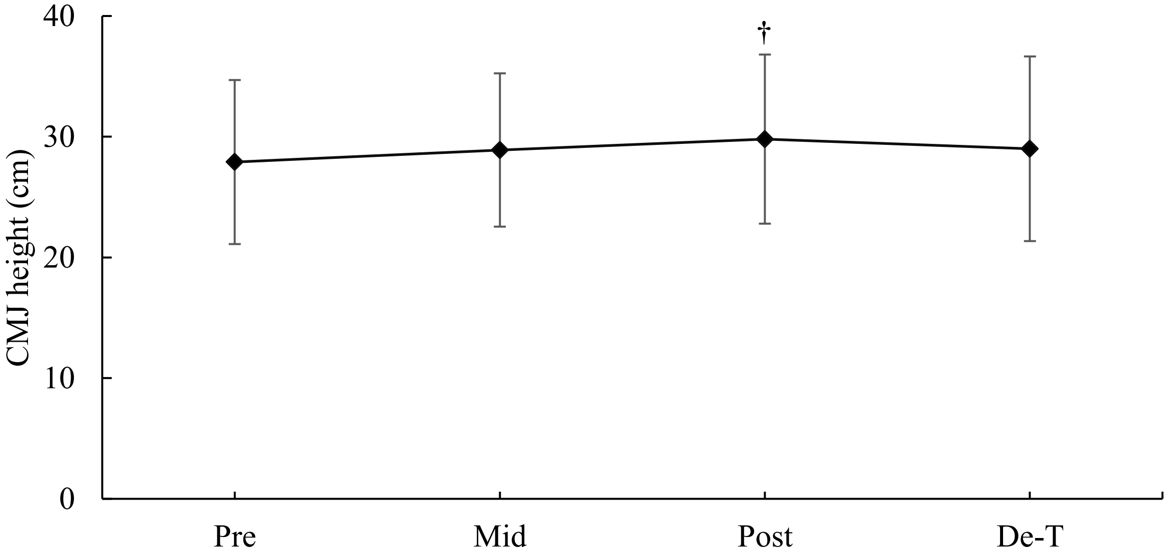

FIGURE 9. Countermovement jump height before training intervention, after 3.5 weeks of training, after 7 weeks of training, and after 5 weeks of detraining. †, significantly different from Pre, $p<0.05$; CMJ, countermovement jump.

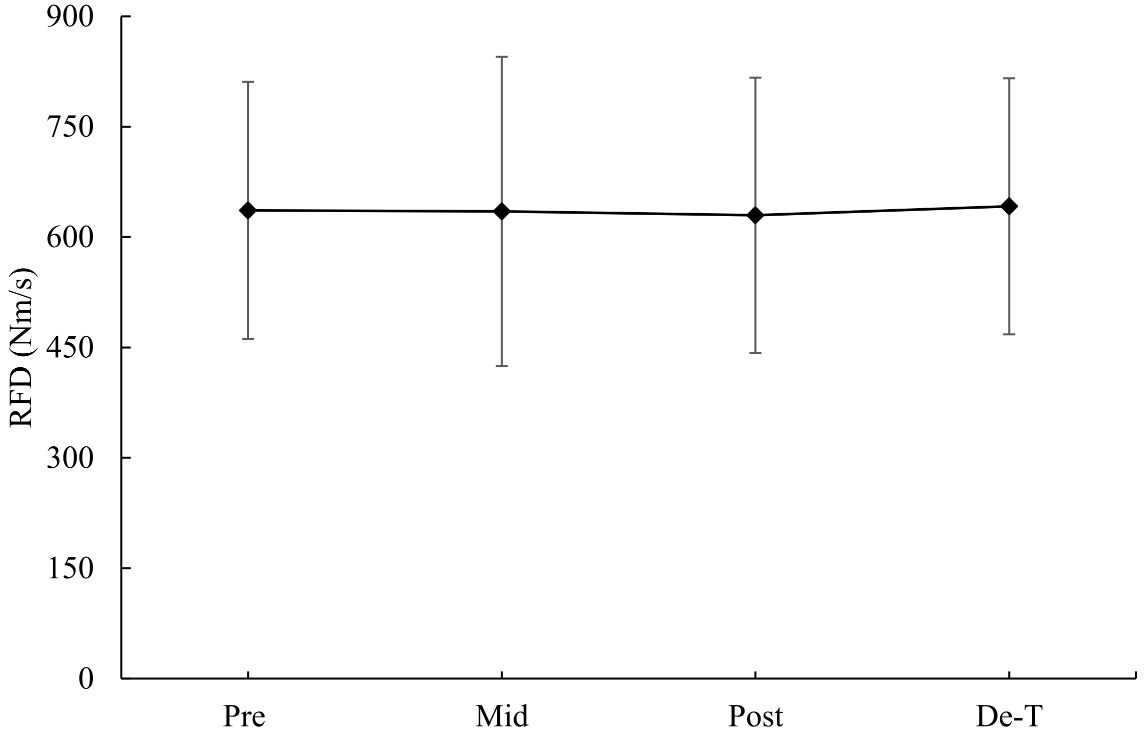

FIGURE 10. Rate of force development before training intervention, after 3.5 weeks of training, after 7 weeks of training, and after 5 weeks of detraining. RFD, rate of force development.

There were significant changes in all variables describing muscle size and architecture between all measurement time-points. VL CSA increased from the baseline to mid measurements and from mid to post measurements, and then decreased in response to detraining (figure 11). VL CSA still remained above the pre-training level after five weeks of detraining (figure 11). VL thickness (figure 12) and PA (figure 13) both increased from baseline to mid-measurements and further from mid to post-measurements. The decrease of both thickness and PA in response to detraining was that extensive that the post detraining values no longer differed from the pre-training level.

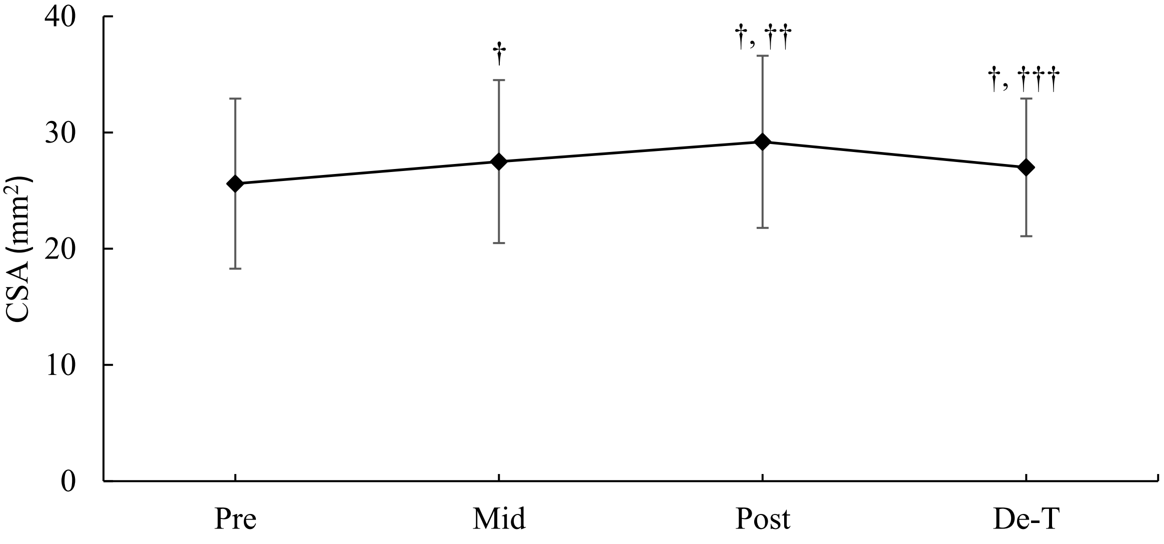

FIGURE 11. Cross-sectional area of vastus lateralis muscle before training intervention, after 3.5 weeks of training, after 7 weeks of training, and after 5 weeks of detraining. †, significantly different from Pre, $p<0.05$; ††, significantly different from Mid, $p<0.05$; †††, significantly different from Post, $p<0.05$; CSA, cross-sectional area.

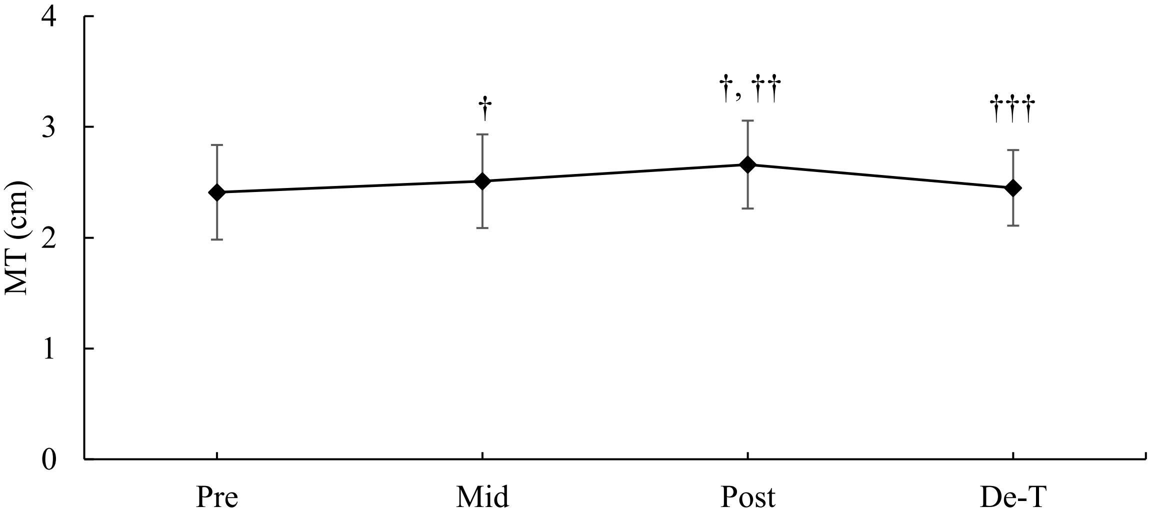

FIGURE 12. Thickness of vastus lateralis muscle before training intervention, after 3.5 weeks of training, after 7 weeks of training, and after 5 weeks of detraining. †, significantly different from Pre, $p<0.05$; ††, significantly different from Mid, $p<0.05$; †††, significantly different from Post, $p<0.05$; MT, muscle thickness.

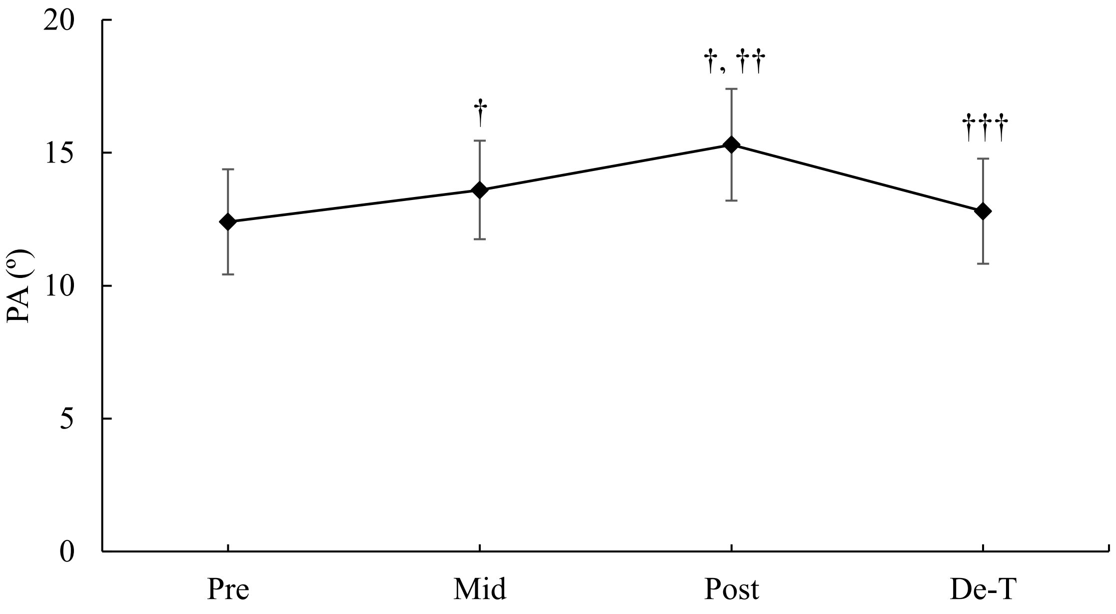

FIGURE 13. Pennation angle of vastus lateralis muscle before training intervention, after 3.5 weeks of training, after 7 weeks of training, and after 5 weeks of detraining. †, significantly different from Pre, $p<0.05$; ††, significantly different from Mid, $p<0.05$; †††, significantly different from Post, $p<0.05$; PA, pennation angle.

The percentual changes of each variable are summarized in table 6. Significant percentual changes were seen in CMJ height, VL CSA, VL thickness, and VL PA.

TABLE 6. Percentual changes of different performance and muscle architecture variables along the training intervention and in response to detraining.

| Variable | Pre-mid Δ% | Mid-post Δ% | Post-DeT Δ% | Pre-post Δ% |
|---|---|---|---|---|
| CMJ | 4.2±7.3 | 2.9±5.0 | -3.0±4.6 | **8.3±12.5*** |
| RFD | -1.6±11.4 | -0.3±9.8 | 1.4±8.1 | -1.9±10.9 |
| CSA | **6.7±4.9*** | **5.9±3.5*** | **-9.0±6.3*** | **14.2±5.9*** |
| MT | **3.5±3.7*** | **5.3±4.2*** | **-8.8±3.4*** | **9.9±6.5*** |
| PA | **9.6±7.9*** | **9.6±8.4*** | **-20.9±10.4*** | **22.5±9.3*** |

CMJ, countermovement jump; RFD, rate of force development; CSA, cross-sectional area; MT, muscle thickness; PA, pennation angle; *, significant change between measurement points ($p<0.05$).

When the correlations between changes in different variables were explored the only detected significant correlations were seen between the changes of VL MT and VL PA in response to both training (figure 12) and detraining (figure 13) periods. There weren't any correlations between percentual changes of explosive strength variables and changes of muscle size or architecture.

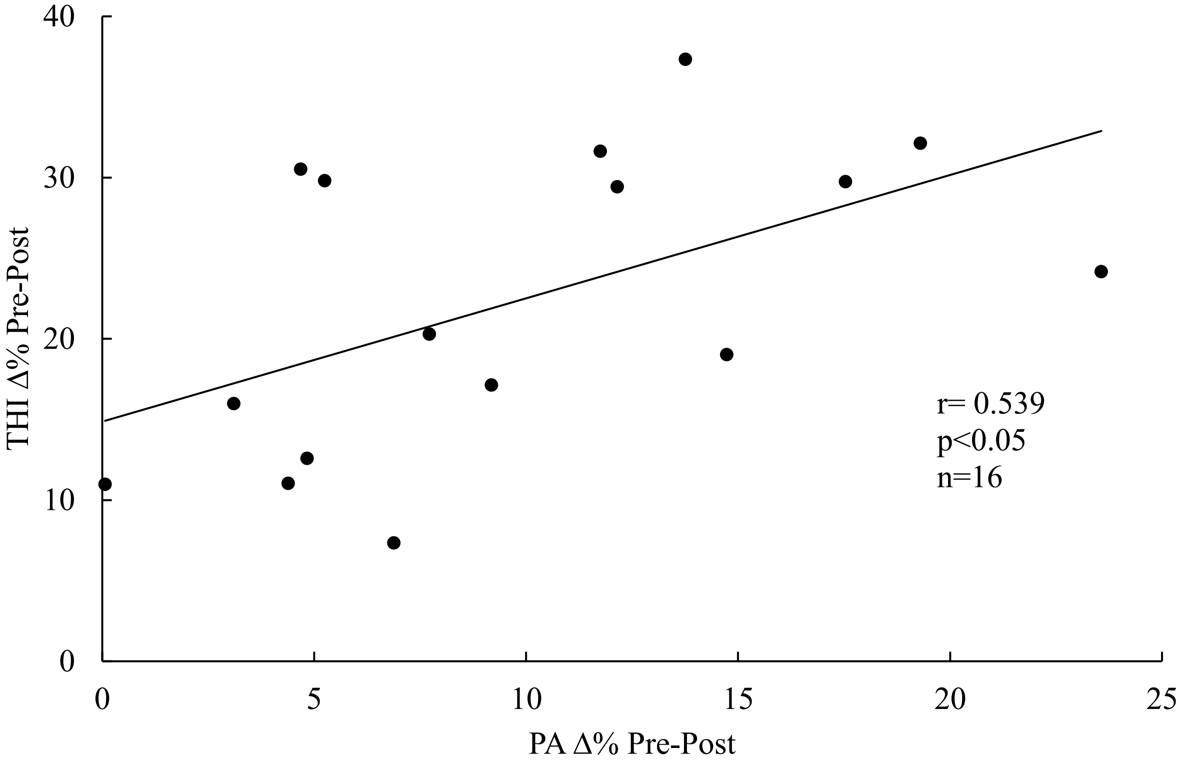

FIGURE 12. Correlation between percentual changes of vastus lateralis thickness and vastus lateralis pennation angle from the baseline to the end of training intervention. MT, muscle thickness; PA, pennation angle.

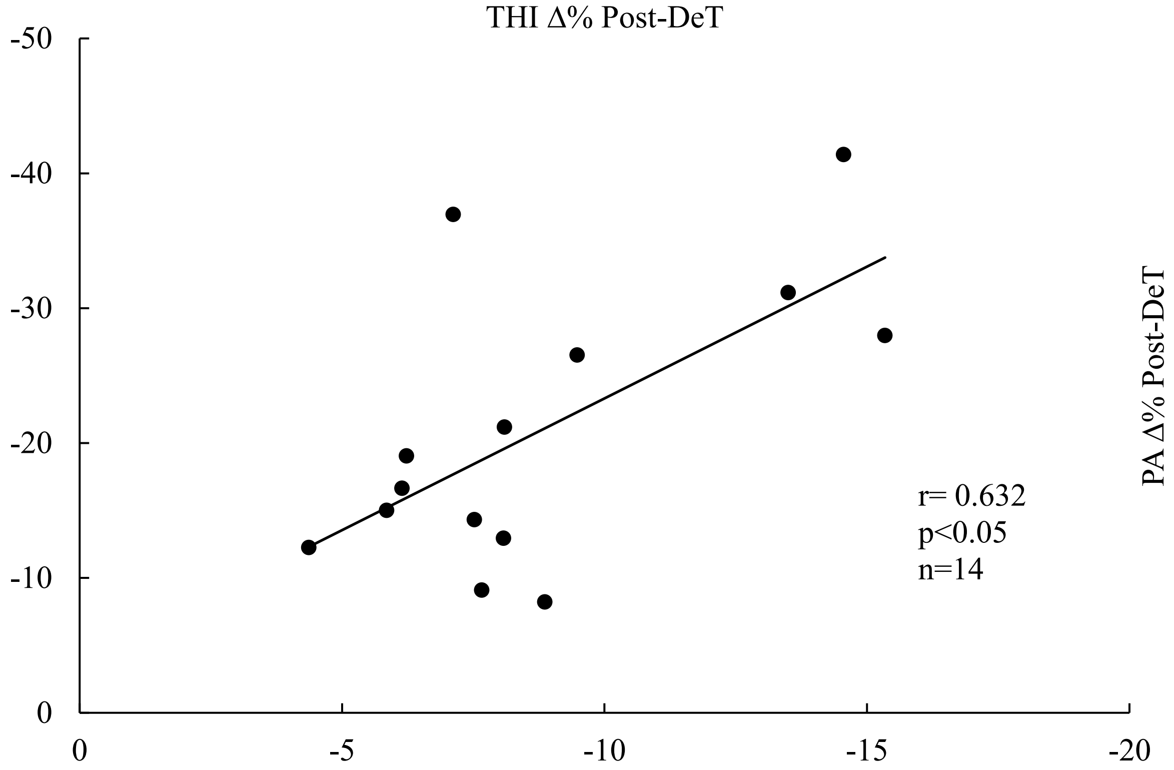

FIGURE 13. Correlation between percentual changes of vastus lateralis thickness and vastus lateralis pennation angle in response to detraining period. MT, muscle thickness; PA, pennation angle.

Pre-training level of both VL CSA (figure 14) and VL MT (figure 15) negatively correlated with the increases seen in the variable in question in response to training. Such correlations were not present for CMJ height, RFD, or VL PA.

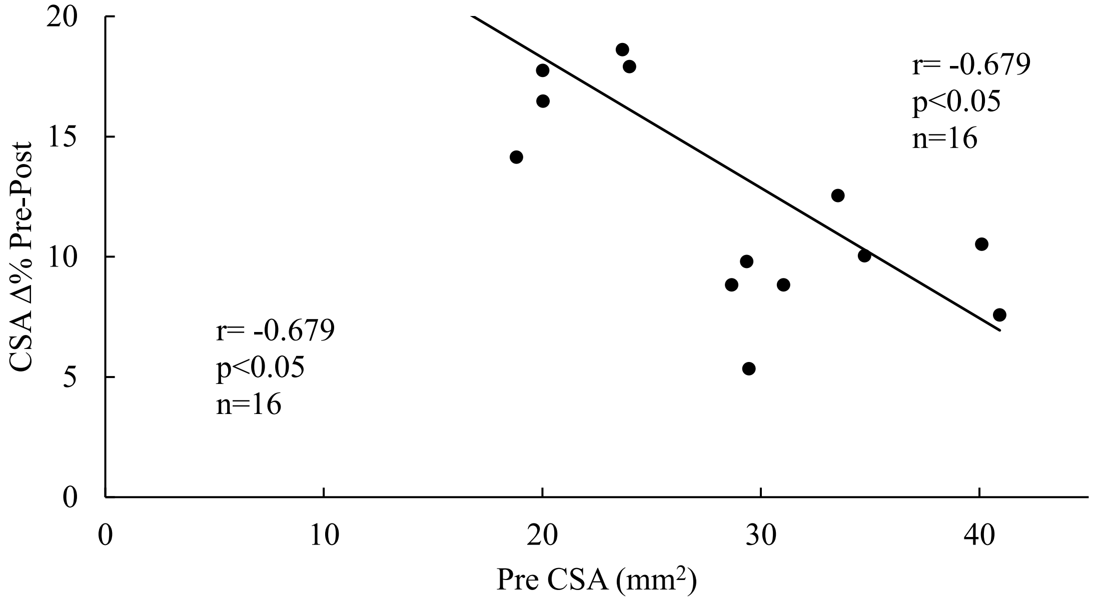

FIGURE 14. Correlation between baseline level of vastus lateralis cross-sectional area and percentual change of vastus lateralis cross-sectional area in response to training intervention. CSA, cross-sectional area.

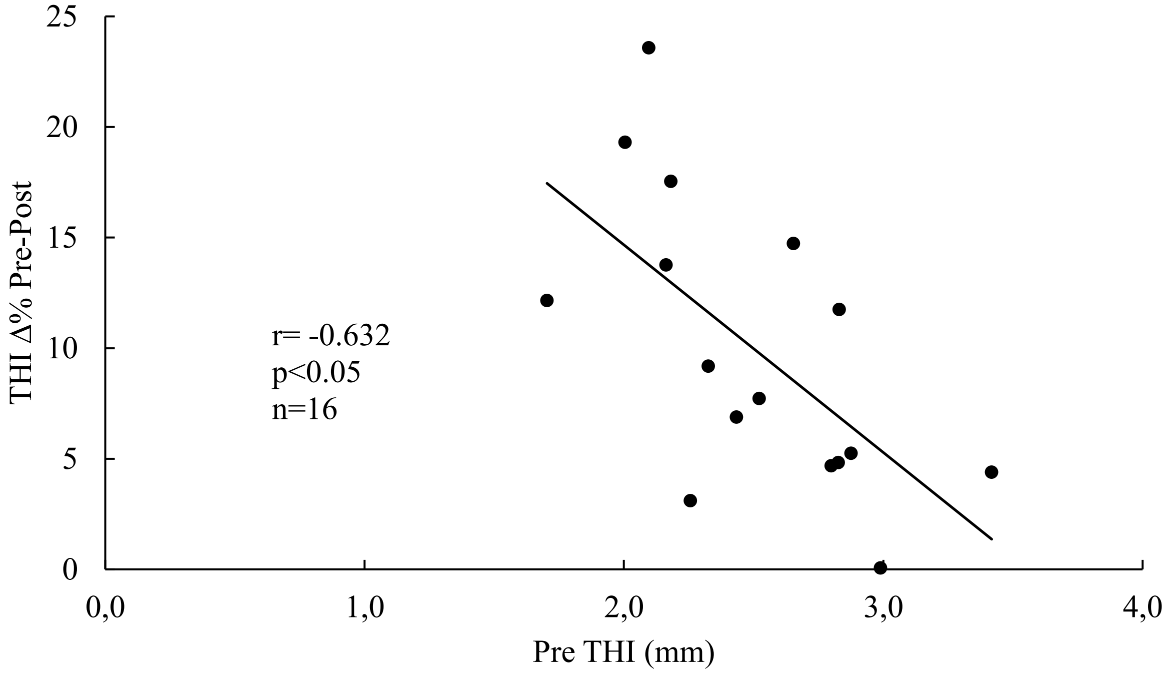

FIGURE 15. Correlation between baseline level of vastus lateralis thickness and percentual change of vastus thickness in response to training intervention. MT, muscle thickness.

Even there weren't any correlations between explosive strength and muscle architecture adaptations there were some correlations seen between performance variables and muscle size at specific timepoints (table 7).

TABLE 7. Observed significant correlations between explosive strength and variables describing muscle size.

| | RFD Pre, CSA Pre | RFD Pre, MT Pre | RFD Mid, CSA Mid | RFD Post, CSA Post | RFD Post, MT Post | RFD DeT, CSA DeT | CMJ DeT, CSA DeT |
|---|---|---|---|---|---|---|---|
| r | 0.757 | 0.534 | 0.635 | 0.655 | 0.535 | 0.655 | 0.582 |
| $p$ | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 |
| n | 17 | 17 | 17 | 15 | 15 | 14 | 14 |

RFD, rate of force development; CSA, cross-sectional area; MT, muscle thickness; CMJ, countermovement jump.

# 10 DISCUSSION

The aim of the study was to characterize the time-course of explosive strength and morphological adaptations in response to combined plyometric and strength training, as well as to study if there are correlations between adaptations in explosive strength and muscle architecture. Of the two variables used to measure explosive strength only one behaved as hypothesised. CMJ height increased in response to training and decreased after detraining, while in RFD there weren't any significant changes during intervention. The significant positive adaptations of VL CSA, thickness, and PA to training were in line with hypotheses. However, the significant decreases of all muscle architecture variables were partly in disagreement with the initial hypotheses. Of the main interest in this study were the possible connections between explosive strength adaptations and morphological adaptations of vastus lateralis muscle, but no correlations were found.

## 10.1 The time-course of explosive strength adaptations to training and detraining

The increase of 8.3% seen in CMJ height in response to 7 weeks of low volume plyometric training combined with moderate intensity concentric-eccentric strength training in the present study is largely in agreement with previous studies. It has been shown in multiple previous studies, that strength training alone is not necessarily specific enough to elicit improvement in jumping performance (Fernandez-Gonzalo 2014; Stasinaki et al. 2019; Vissing et al. 2008). Methenitis et al. (2020) have demonstrated that during combined plyometric and strength training the training volume centrally affects the extent of adaptations, as with lowest volume CMJ height increased by 15%, with moderate volume by 9% and with highest volume by 7%. In the present study there were 8 sets of lower body exercises per session which falls between the moderate and high volume training reported by Methenitis et al. (2020), and thus the results are very much alike. Comparably, the non-significant decrease in CMJ height to a level not significantly different from the pre-training values stimulated by a 5-week detraining period in the present study resembles the results seen before. Short detraining periods of 3 (Gavanda et al. 2020) or 4 (Branquinho et al. 2020; Sousa et al. 2018) weeks have been reported to cause either a significant decrease or atleast a decreasing trend in CMJ height so that after detraining the performance no more differed from the pre-training level.

The non-significant changes in RFD250 seen in this study somewhat contradicts the results of previous studies where training interventions of as short as 4 weeks (Tillin et al. 2012; Tillin & Folland 2014) have elicited significant improvements. It needs to be noted that in those studies both training and performance testing was isometric. Thus, one possible explanation for the inconsistency between the present results and the previous literature is that the isometric type testing wasn't specific enough to detect performance adaptations caused by concentric-eccentric training. However, also dynamic strength training interventions have been reported to stimulate significant improvements in isometric late phase RFD, but those interventions seem to be of eccentric type training (Methenitis et al. 2020; Stasinaki et al. 2019) or of longer duration ranging from 12 to 14 weeks (Aagaard et al. 2002; Andersen et al. 2010). The superiority of low training volume and high training intensity for extensive RFD adaptations has also been pointed out in several studies (Balshaw et al. 2016; Methenitis et al. 2020).

Peltonen et al. (2018a) have demonstrated that there are significant inter-individual differences in how explosive strength measured as peakRFD10 adapts in response to different types of strength training. Three different adaptation patterns included significant improvement in response to maximal strength training period, significant improvement in response to power training period, and no significant improvement in response to either maximal strength or power training period. In non-responders there even was a decrease in response to maximal strength training period. (Peltonen et al. 2018a) As in the present study the results were interpreted only at a group level it is possible that the presence of different responders in the same group contributed to non-significant changes along the intervention. Finally, it should be noted that in literature RFD testing has been described to be able to detect training induced adaptations only when testing is specific enough compared to training. Only unilateral training appears to elicit improvements in unilaterally tested RFD (Bogdanis et al. 2019a) in addition to that RFD adaptations seem to be relatively joint angle specific (Bogdanis et al. 2019b). Thus, non-signifant changes in RFD in the present study may also be due to insufficient specificity of the utilized RFD testing protocol.

## 10.2 The time-course of morphological adaptations to training and detraining

The increase of VL CSA by 14.2% seen in present study is largely in accordance with previous studies. For example, Zaras et al. (2021) reported an increase of 16.7% in response to 7 weeks of training, Sterczala et al. (2020) an increase of 18.7% in response to 8 weeks of training, and Santanielo et al. (2020) an increase of 18.1 % in response to 10 weeks of training. As previous studies have reported significant adaptations already after 3 (DeFreitas et al. 2011) or 4 (Baroni et al. 2013; Boone et al. 2005) weeks of training the present finding regarding CSA adaptations following 3.5 weeks of training is also in accordance with previous literature. In the present study CSA continued to increase from mid measurements to post measurements without any alterations in the training program except for the increased training loads. Also Baroni et al. (2013) and DeFreitas et al. (2011) have reported continuous adaptations in VL CSA without training program modifications for 8 and 7 weeks, respectively.

The present finding of CSA decrement in response to 5 weeks of detraining is in accordance with results by Kubo et al. (2010) who reported a decrease to a level not significantly different from pre-training level after 4 weeks of detraining. In a recent study by Räntilä et al. (2021) the individuality of hypertrophic adaptations to both training and detraining was investigated, and it was found that those who show high responses to training tend to also be affected most by detraining. Although the individual adaptation patterns were not under the scope in the present study it is justified to assume that the subjects still have adapted to training differently. An another aspect that needs to be taken into account when comparing the VL CSA adaptations reported in different studies, is that morphological adaptations appear to differ between different sites of VL both longitudinally (Bloomquist et al. 2013) and transversely (Wells et al. 2014).

The significant increases seen in VL MT in mid-measurements and further in post-measurements largely support the previous finding, that MT adapts to strength training within weeks in previously untrained. Tillin et al. (2012) reported that MT increased by 7% in response to 4 weeks of isometric training while in the present study combined plyometric and strength training stimulated an increase of 3.5% after 3.5 weeks and a total increase of 9.9% in response to 7 weeks of training. Similar adaptation have been reported after training interventions utilizing differing training modes, however certain types of training have been shown to be more preferable to stimulate increases in MT. Stasinaki et al. (2019) reported increase in MT (6%) only after 6 weeks of slow but not fast eccentric training and Blazevich et al. (2007a) demonstrated somewhat differing adaptations in MT after 10 weeks of either eccentric (8.3%) or concentric (11.8%) training. Thus, when comparing the percentual or absolute changes reported in different studies it is important to be aware of the effects of even slight alterations in training programs on the morphological adaptations. Significant differences in VL MT adaptations have also been reported when they are measured at different locations along the VL muscle (Wells et al. 2014).

The present results of the effects of detraining on MT somewhat contradict the previous results. Gavanda et al. (2020) reported that 3 weeks of detraining had no effects on MT while in this study MT decreased by 8.8%. Also significantly longer detraining period of 3 months have been reported to cause only a non-significant decrease of MT still resulting the post-detraining values to no more differ from the pre-training level (Blazevich et al. 2007a). However, in both of the aforementioned studies the initial training period was longer (10 to 12 weeks) than in the present study which may have contributed to the differing results.

Several previous studies examining the effects of short term strength training have failed to show any adaptations in VL PA (Blazevich et al. 2007b; Stasinaki et al. 2019; Tillin et al. 2012) which makes that the present finding of increased PA in 7 weeks somewhat contradicts the literature. However, similar findings also exist. Blazevich et al. (2007a) reported that PA increased after 5 weeks of concentric (11.1%) and eccentric (11.5%) training, while in the present study PA increased by 9.6% for mid-measurements and by 22.5% in total. Concentric training has been reported to be more effective in stimulating PA adaptations in comparison to eccentric training (Franchi et al. 2014). That might partly explain why in this study increases were seen already after 3.5 weeks of concentric-eccentric training while 6 weeks of solely eccentric training didn’t cause any adaptations (Stasinaki et al. 2019).

It has also been demonstrated previously that there appears to be some sex differences in PA adaptations. Significant increases in PA was detected only in women (14%) but not in men (5%) in response to 8-week training intervention. However, it was aknowledged that the baseline values were lower in women which led to conclusion that the PA adaptations were either sex or baseline-related. (Coratella et al. 2018) In the present study subjects were both men and women but sex differences were not examined due to small sample size. Still, the correlation between baseline value and achieved adaptations was analyzed for all variables. Adaptations in muscle size were found to be baseline related while PA or performance weren't. The effect of detraining on PA is relatively poorly studied. Blazevich et al. (2007a) reported that 3 months of detraining significantly decreased PA to a level corresponding the baseline value. In the present study it was demonstrated that 5 weeks of detraining had similar effect as it decreased PA by 20.9% and thus PA no more differed from pre-training value.

The influence of baseline level of explosive strength and muscle architecture on the extent of training-induced adaptations in untrained subjects has not been widely studied. There are some studies supporting the notion that baseline strength (Mangine et al. 2018) or muscle architecture variables (Coratella et al. 2018) may affect the adaptations. Therefore, the negative correlations between baseline CSA and MT and their adaptations to training seen in the present study may add something to the current notion about the topic. Significant correlations between the percetual changes of each measured variables was found only between MT and PA. The adaptations to training as well as to detraining correlated (r=0.539 and r=0.632, respectively). The positive correlation between MT and PA of pennated muscles is widely identified, and for example Kawakami et al. (2006) reported a correlation of 0.61 in a cross-sectional study where the muscle architecture of VL of several hundred people of different training backgrounds was studied.

### 10.3 Correlations between explosive strength and muscle architecture

As already mentioned, there were no correlations between performance adaptations and morphological adaptations. As the only longitudinal connections between explosive strength and muscle architecture reported in previous studies have been between RFD and FL (Zaras et al. 2016) or RFD and MT (Stasinaki et al. 2019), it is understandable that no connections were seen in this study where RFD didn't significantly change and FL couldn't be analysed from the collected data. To allow analyses of FL from ultrasound data with certainty, there should have been images taken longitudinally along VL with extended field of view. The present images turned out to be of too low quality to permit reliable analysis of FL.

The correlations between explosive strength and muscle size in specific time points were expected based on observed connections in previous cross-sectional studies (Coratella et al. 2020; Secomb et al. 2015). CMJ height has not been widely reported to correlate with VL architecture. A meta-analysis about the influence of VL muscle morphology on CMJ height showed a correlation only between VL MT and CMJ height (Ruiz-Gardenaz et al. 2018). In individual studies VL architecture has tended to not show correlations for CMJ height, but other variables like lateral gastrocnemius architecture (Earp et al. 2010), type II fibre CSA (Methenitis et al. 2016), or jumping technique (Cormie et al. 2009). The importance of type IIx fibre percentual area for RFD has been demonstrated (Andersen et al. 2010) but there are also results suggesting that quadriceps muscle architecture correlates with RFD. VI MT has been shown to correlate (0.54-0.63) with different RFD variables (Coratella et al. 2020) and in the present study VL MT correlated with RFD250 before (r=0.534) and after (r=0.535) the training intervention. Late phase RFD has been shown to be influenced by maximal force and is thus also linked to muscle mass (Andersen et al. 2010). Thus, positive correlations found in the present study between CSA and RFD in all of the measurement points (r=0.635-0.757) are in accordance with literature. Nevertheless, direct correlations between RFD and muscle size have not been reported frequently in previous studies in young, healthy and untrained populations.

## 10.4 Interpretation of the results

Certain aspects should be taken into consideration when interpreting the results of the present study. Firstly, it is important to notice that there were several variables that certainly influence explosive strength that however were not measured in the present study. For example, the role of muscle fibre type composition and especially the proportion of fast muscle fibres in fast force production has been identified in previous studies (Andersen et al. 2010; Mathenitis et al. 2020).

Secondly, muscle size and muscle architecture were measured only from vastus lateralis due to practical reasons, even though other muscles influence both isometric and dynamic explosive strength (Coratella et al. 2020; Earp et al. 2010). Interestingly, it has also been demonstrated that training-induced adaptations may differ at different sites of muscle, and that all adaptations do not correlate with performance (Wells et al. 2014).

Thirdly, it is beneficial to be aware of the possible effects of having men and women combined to a one experimental group. The relatively low amount of subjects and inclusion of two sexes in same group resulted in a small heterogenous sample in the present study. Previous studies examining the possible sex differences suggest that in explosive strength adaptations there necessarily isn't any differences (Fernandez-Gonzalo et al. 2014) while in morphological adaptations there appears to atleast some sex-dependance (Coratella et al. 2018). Finally, the formula used to calculate individual training loads turned out to be more accurate for multi-joint exercises included in training program than what it was for single-joint exercises. In consequence of that the relative training intensity in every exercise and in every training session was not what it was supposed to be. It is possible that varying relative loads have had minor effects on training adaptations.

### 10.5 Strengths and limitations of the study

One of the strengths of this study is that it's among the first to describe the time-course of explosive strength and muscle architecture adaptations. Especially, research on the effects of short-term detraining period on the variables included in the present study is scarce. Having both men and women included in the study is both a strength and a weakness. Many previous studies have had only male subjects. Including also female in the present study widens the understanding of the different training-induced adaptations. However, more valuable information would have been obtained if the sample size had allowed comparison between sexes. Thus, relatively small sample size is one of the limitations in the present study. One of the weaknesses is also the aforementioned issue with the formula used for defining the loads. Finally, the measurement protocol for RFD was not optimal for detecting the adaptations induced by this specific training program taking into consideration the high specificity of RFD adaptations discussed earlier.

## 10.6 Conclusions

The present study failed to show any connections between explosive strength adaptations and morphological adaptations. It can be argued to be partly due to the insufficient ability of the training program to induce extensive adaptations in explosive strength. However, as there still was a significant improvement in one of the two measured explosive strength variables, that was not connected to adaptations of any of the measured variables of muscle architecture, it can be proposed that changes in other factors than muscle morphology, most probably neural ones, largely induce the early adaptations of explosive strength in previously untrained subjects. Still, the findings of the present study should be verified in future studies with care taken that the training program is specifically designed to induce adaptations in explosive strength, and that explosive strength is measured in a way that sufficiently corresponds to the way it is trained, and muscle architecture is measured so that it enables the analysis of changes in fascicle length.

Regardless of certain limitations in the implementation of this study, the study succeeded to provide novel information about the time-course of morphological adaptations in previously untrained subjects. It was shown that 3,5 weeks of combined plyometric and conventional strength training with a frequency of 2 times a week is sufficient to induce increases in CSA, MT, and PA of VL. All aforementioned muscle architecture variables continued to increase in response to another 3,5 weeks of training with subjects following the same training program with adjustments only in training loads. Thus, it can be concluded that the training program doesn’t necessarily need to be modified within the first 7 weeks to induce continuous morphological adaptations in untrained subjects. Including a detraining period to the study design revealed that 5 weeks of detraining caused significant decrease in all of the studied variables describing muscle architecture. The results suggest that CSA adaptations may be retained somewhat better in comparison to adaptations in MT and PA. All in all, training cessation of 5 weeks or longer should be avoided if the gained adaptations in muscle architecture are aimed to maintain.

## 10.7 Practical applications

Based on the findings of the present study it can be concluded that combined plyometric and strength training stimulates adaptations in CMJ height and muscle architecture in previously untrained subjects. In untrained subjects a training program does not necessarily need to be modified in addition to increased loads within first seven weeks of training. When more extensive explosive strength adaptations are pursued a more specific training program probably with a lower training volume should be preferred. The inability of the used RFD test protocol to detect changes in isometric explosive strength performance underlines the importance of specificity of explosive strength testing. Detraining of five weeks causes a decreasing trend in CMJ height and significant regression of morphological adaptations, but it still needs to be studied how those adaptations are regained in response to retraining.

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