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**Short- versus full range of motion
explosive training to enhance lower
limb power production**

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Abstract

Introduction: Resistance training for sports requiring explosive movements is often performed over the full range of motion (ROM). Interestingly, training with either explosive dynamic or isometric contractions have showed to result in similar increase in dorsiflexor torque at high velocity and rate of torque development (RTD). The purpose of this study was to test the hypothesis that explosive full ROM and very short ROM knee extensions would result in similar increase in isokinetic full ROM knee-extension torque and power production in leg press.

Method: Sixteen volunteers underwent a 10-week resistance training program using a leg press machine. Training was performed unilaterally, with each leg assigned to very short ROM or full ROM, explosive contractions. Both legs were exercised from 90° knee-flexion (180° = extended knee). Measurements included muscle architecture (vastus lateralis), voluntary and electrically induced RTD of knee extensor muscles, and isokinetic knee-extension torque at 30°s⁻¹, 60°s⁻¹, 180°s⁻¹ and 300°s⁻¹. In addition, peak power and force were measured during full ROM leg press (80-180° knee angle).

Results: The two training schemes resulted in similar functional improvement in leg press and isokinetic knee extensions. Both training modalities led to similar increase in power at various loads configurations, and a greater isokinetic knee-extension torque at 180°s⁻¹ and 300°s⁻¹, but not at lower velocities. Voluntary and electrical evoked knee extension torque increased in both training modalities, however, very short ROM training led to a significant greater improvement in voluntary torque at 150 ms after torque onset.

Conclusion: These results extend previous findings by showing that explosive resistance training of the knee-extensors muscles lead to similar adaptations, irrespective of the ROM during the training. The functional improvement at higher velocities is thought to be associated with the increase in RTD. The greater RTD is ascribed to neural and muscular adaptations improving rapid force production in the early phase of the ROM, when most of the muscle force and work can be produced. Hence, owing to the greater work produced by the muscle fibers in the initial part of the contraction, explosive training with very short ROM contractions may be just as effective as dynamic contractions to improve functional performance over full ROM.

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1. Introduction

In explosive sports such as running and jumping, the ability for the athlete to develop high power and impulse is essential for performance. In such sports, the time window to develop force is limited to 50-to-250 ms (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002). In contrast, maximal contractile force is reached at or after 300 ms during isometric contractions (Hill, 1938; Aagaard et al., 2002). Therefore, power and impulse production in explosive movement is highly conditioned by the capacity to produce force as fast as possible (i.e., rate of force development (RFD)). The rate of force development is influenced by several factors often categorized as neural and muscular determinants (Maffiuletti et al., 2016).

Resistance training has shown to lead to both neural and muscular adaptations which contribute to increases in RFD (Duchateau & Hainaut, 1984; Folland & Williams, 2007; Tillin & Folland, 2014; Aagaard, 2003; Aagaard et al., 2002) in a manner specific to training modalities (Duchateau & Hainaut, 1984). Resistance training is often performed at high velocity in studies aiming at improving performance in explosive sports (Cormie, McGuigan, & Newton, 2010, 2011b; Wilson, Newton, Murphy, & Humphries, 1993). High-velocity resistance training is thought to lead to velocity specific improvement in power production by increasing shortening velocity and torque at higher velocities (Duchateau & Hainaut, 1984). However, Behm and Sale (1993a) reported that both explosive isometric and dynamic contractions led to a similar improvement in voluntary and electrical evoked isometric rate of torque development and dynamic dorsiflexion torque. Behm and Sale (1993a) suggested that regardless of the joint operating range, training with high RFD would lead to similar adaptations that increase the force production in high-velocity movements, although the underlying mechanisms were unclear.

The understanding of muscle behaviour during dynamic movement has evolved in recent years. The development and improvements of technology have made it possible to investigate the behaviour of the muscle-tendon unit *in vivo*. Studies have shown that during dynamic movements, most of the shortening and work production of the muscle occurs in the early part of the range of motion (ROM) (Kurokawa, Fukunaga, &

Fukashiro, 2001; Nikolaidou, Marzilger, Bohm, Mersmann, & Arampatzis, 2017). The muscle capacity to develop high force in the initial part of the ROM is therefore crucial for impulse and power production in explosive dynamic movements, which could explain the findings from Behm and Sale (1993a). The use of high-load resistance training for improving force-production at higher-velocities may have interesting implications for athletes wishing to maintain or develop maximal force production. However, the observations reported by Behm and colleagues stem from isometric or isokinetic dorsiflexion contractions, with a starting position of 30° in plantarflexion (0° as the anatomical angle). While this unusual setup probably favored training at high velocity, it makes any extrapolation to locomotor task difficult. Additionally, the extent to which familiarization gained from training and being tested with the same equipment may have masked some of the specific adaptations caused by each training regimen is unknown.

1.1. Purpose

The main purpose of this study was to investigate whether the findings by Behm and colleagues could be applied to larger muscles with a more significant contribution to locomotor work. A secondary aim was to determine whether very short or full ROM resistance training induces different adaptations in the parameters related to RTD. To this end, unilateral explosive resistance training of the knee extensor muscles was undertaken with a leg press apparatus with each leg assigned to full ROM or very short ROM (~10°). To determine if there was a ROM specific adaptation, muscle function was examined during isokinetic knee extensions and full ROM leg press.

1.1.1. Hypotheses

1. By a similar improvement in force production at the beginning of the contraction, explosive very short ROM training improves power output in a dynamic movement just as effectively as explosive full ROM training.
2. Both training modalities lead to a similar increase in isometric rate of torque development.
3. Both training modalities will lead to similar adaptations in the parameters enabling high rates of torque development.

2. Theory

The muscle has several functions in the body such as produce mechanical work, and assist in thermoregulation (Jensen, Rustad, Kolnes, & Lai, 2011; Zatsiorsky & Prilutsky, 2012). Additionally, the muscle contains the ability to cope with a broad range of activities, from supporting the body mass to contribute to explosive movements (Westerblad, Bruton, & Katz, 2010). Performance in explosive sports depends on the ability of the muscle to develop high force at high velocities. The muscle's ability to contract with high force and high velocity is often referred to as power. Power is defined as the product of force and velocity i.e. the amount of work performed per unit of time. The ability to develop high power depends on several physiological factors often categorized as neural and muscular determinants (Cormie, McGuigan, & Newton, 2011a). The importance of these factors has shown to vary depending on the time available to produce the force (Andersen & Aagaard, 2006; Folland, Buckthorpe, & Hannah, 2014). The following section aims to present the muscle structure and the current knowledge about factors that influence power production. Moreover, the typical adaptations reported after dynamic and isometric resistance training regimes are described.

2.1. Muscle structure

The muscle's ability to create force and mechanical work is due to the contractile proteins actin and myosin (McArdle, Katch, & Katch, 2007). Actin and myosin together with the z-membranes make up most of the sarcomere. The striated structure consists of repeating arrays of actin and myosin filaments which is partly overlapping and connected through cross-bridge shaping myofilaments (Huxley, 1957). The interaction between myosin heads and the actin results in sarcomere shortening and force generation. This process is known as the sliding filament theory (Huxley, 1969). It has recently been shown that titin also influences the force production (Herzog, 2018). However, the importance of titin on the muscle force-producing capacity is still not fully understood. Furthermore, the muscle is divided into different layers, many sarcomeres make up the myofibril, and thousands of myofibrils form a muscle fiber i.e. muscle cell (Lieber & Fridén, 2000). The muscle fibers are enclosed by a membrane

named sarcolemma, which is surrounded by endomysium (McArdle et al., 2007). Many muscle fibers form one fascicle that is enclosed by perimysium. Finally, the whole muscle is surrounded by epimysium (Zatsiorsky & Prilutsky, 2012).

2.2. Muscle contractile properties

The muscle contains contractile properties that influence the force-production. The shortening-velocity of the sarcomeres influences the muscle ability to develop force. The relationship between force and velocity was first presented by Hill (1938) and is referred to as Hill's curve or the force-velocity relationship. The force-velocity relationship is characterized by an exponential decrease in force production when shortening velocity increases (Fenn & Marsh, 1935). When contraction velocity increases, the time needed to develop cross bridges between the myofilaments is reduced, which will result in a decreased number of active cross-bridge cycles. Since the amount of force created by the muscle depends on the numbers of attached cross-bridges, force production decreases when contraction velocity increases (Lieber, 2010). The force-velocity relationship represents a specific property of the muscle that dictates its power-producing capacity (Cormie et al., 2011a). The power production is maximized at a submaximal force and velocity value (figure.1). Peak power is typically achieved at a velocity which correspond to 1/3 of maximal shortening velocity (Cormie et al., 2011a). Numerous factors influence the force-velocity relationship, such as muscle fiber composition (MacIntosh, Herzog, Suter, Wiley, & Sokolosky, 1993), muscle architecture (Lieber & Fridén, 2000) and neural activation (Caiozzo, Perrine, & Edgerton, 1981).

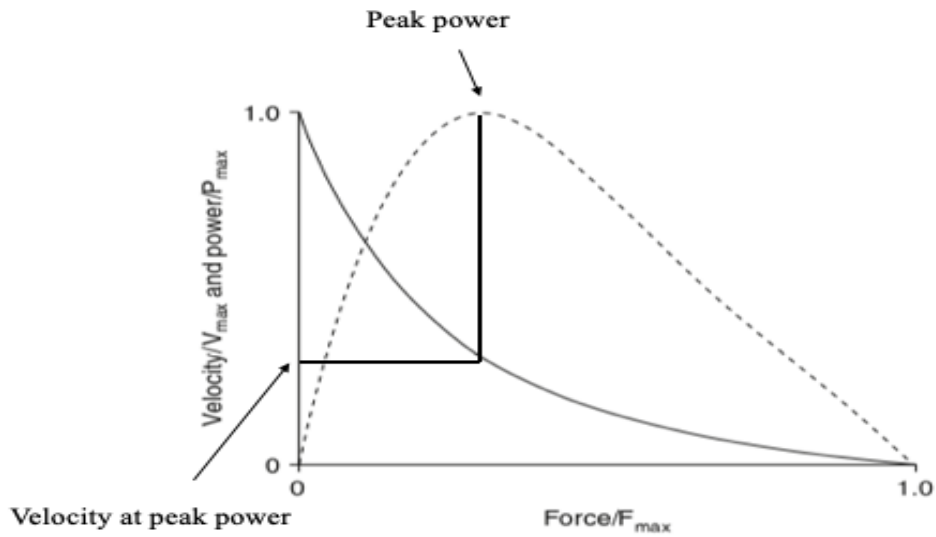


Figure 1. *The force-velocity and force-power relationship for contractions of skeletal muscle. Force is normalized to the maximum isometric force, velocity is normalized to maximum velocity of shortening and power is normalized to maximum power output. Figure reproduced from Cormie et al. (2011)*

The ability to develop force is influenced by the total amount of cross-bridges between actin and myosin (Rassier, Macintosh, & Herzog, 1999). The muscle's force-producing capacity is length dependent, due to a variation of actin and myosin interactions in a contraction. This relationship is known as the force-length relationship (Gordon, Huxley, & Julian, 1966). The highest potential for force-production occurs when there is an optimal overlap between actin and myosin (Gordon et al., 1966). At this length, the interaction between the contractile filament is optimal, which allows for maximal force production. A shortening of the sarcomere beyond the optimal length will lead to a compressed sarcomere, which will lead to a suboptimal potential for force-production (Lieber, 2010). Stretching the sarcomere beyond the optimal length will result in a reduced interaction between the contracting filaments (Lieber, Loren, & Friden, 1994). The force-length relationship will influence the muscle ability to develop force, and therefore affect the muscle power production (Cormie et al., 2011a).

2.3. Muscle morphology

2.3.1. Muscle fiber type

The ability to develop contractile force is also influenced by muscle fiber type. The muscle consists mainly of three different muscle fibers, type I, IIa and IIx (Westerblad et al., 2010). The contractile properties of the different muscle fiber types have somewhat different characteristics. The maximal isometric force production is similar between the different muscle fibers when normalizing the force to the muscle fiber cross section area (Fitts & Widrick, 1996). However, when shortening velocity increases, the maximal force production is considerably higher in types IIa and IIx compared with type I. This is mainly due to that type II fibers have a greater maximal shortening velocity, which results in a faster cross-bridge cycle and thereby a greater rate of force development. This phenomenon is due to greater calcium release per action potential (Baylor & Hollingworth, 1988) and faster calcium current, as well as faster myosin isoforms, troponin, and tropomyosin in type II fibers (Close, 1972; Schiaffino & Reggiani, 1996). The muscle fiber type composition will, therefore, have a significant influence on the power production especially when contraction velocity increases.

2.3.2. Muscle architecture

The muscle is highly organized not only at the microscopic level but also at the macroscopic level also known as the muscle architecture (Lieber & Fridén, 2000). The organization of muscle architecture has a great influence on the muscle's contractile properties (Burkholder, Fingado, Baron, & Lieber, 1994; Lieber & Fridén, 2000). There are mainly three components which need to be taken into consideration regarding the muscle architecture: (1) the muscle cross section area (CSA), (2) the fascicle length, and (3) the pennation angle of the fibers.

The maximal force created by a single muscle fiber is directly proportional to its CSA (Cormie et al., 2011a). A muscle with bigger CSA compared with a smaller muscle has more sarcomeres in parallel, thus a greater amount of active cross-bridges. Concerning the contractile properties of the muscle, a muscle with greater CSA will produce higher force at all contraction velocities and all muscle lengths, as long as all other factors such

as muscle fiber composition, neural activation, fiber length, and pennation angle are identical (Lieber & Fridén, 2000). The relationship between maximal strength and RFD increase in a sigmoidal manner when time from contraction onset increases (Andersen & Aagaard, 2006). This indicates that other factors determine the force producing capacity of the muscle in the initial phase of the force-time curve (Maffiuletti et al., 2016; Mirkov, Nedeljkovic, Milanovic, & Jaric, 2004). As explained, power production at high velocities are mainly influenced by the early phase of RFD. Thus, maximal strength has a greater influence on the power production at slower velocities when the time to produce the force is not limited (Duchateau & Hainaut, 1984).

The length of the fascicle influences the contractile properties of the muscle. A muscle with longer fascicle will have a higher maximal shortening velocity and be able to produce more force at all contraction velocities, as long as all other factors are identical (Lieber & Fridén, 2000). Longer fascicles have more sarcomeres in series, which will result in each sarcomere having a slower absolute velocity, allowing each sarcomere to stay higher on its force-velocity curve (Lieber & Fridén, 2000). Thus, longer fascicles are thought to be more favorable for power production. Some studies have reported that the length of the fascicle may be a determinant for performance in explosive sports. For instance, Abe, Fukashiro, Harada, and Kawamoto (2001) reported that world-class sprinter possesses longer fascicles compared with slower sprinters. The fascicle length is also shown to influence the force-length relationship. A muscle with longer fascicle is able to operate over a longer range (Lieber & Fridén, 2000).

The orientations of the fascicle relative to the muscle axis of force generation are defined as the pennation angle (Lieber & Fridén, 2000). An increased pennation angle allows more muscle fibers along the longitudinal axis of the muscle (Lieber & Fridén, 2000), which increases the physiological cross-section area (PCSA) and thereby the maximal force capacity (Ikai & Fukunaga, 1968; Wickiewicz, Roy, Powell, & Edgerton, 1983). A downside with pennate design compared with parallel fascicle arrangements is that the force is not transmitted in the line of the muscle force axis. Thus, the force produced from parallel muscle fibers will be transmitted more effectively to the tendon (Azizi, Brainerd, & Roberts, 2008), which is thought to be

beneficial for RFD (Erskine, Fletcher, & Folland, 2014). However, when the muscle is shortening, the pennate muscle fibers will rotate which will increase the pennation angle even more. Due to this rotation, the shortening velocity of the whole muscle can exceed the velocity of the muscle fibers, meaning that the muscle can function at a higher gear ratio (Azizi et al., 2008). This velocity-amplification can, in theory, influence the muscle rate of force development for a given shortening velocity (Rodriguez-Rosell, Pareja-Blanco, Aagaard, & Gonzalez-Badillo, 2017). The understanding about how pennation angle influences RFD is not fully understood and needs to be investigated further.

2.4. Neural factors

The ability to develop contractile force is not only influenced by muscular, but also neural factors. The nervous system regulates the muscle activation primarily by, motor units recruitment, action potential firing frequency, motor unit synchronization, and inter-muscular coordination (Cormie et al., 2011a).

A motor unit is defined as one motor neuron and its innervated muscle fibers. The average number of fibers innervated by a motor neuron is ~ 300, but the range extends from tens to thousands (Enoka & Fuglevand, 2001). There are mainly three types of motor units, and they are often classified after their size (Latash, 2008). Motor units innervating type I muscle fibers are the smallest, while motor units that innervate type IIa and IIx are bigger (Egan & Zierath, 2013; Latash, 2008). The motor units are recruited according to the “size principle”: Smaller motor units are recruited at low forces, as the contraction intensity increases the larger motor units are recruited (Henneman & Olson, 1965). Thus, the relative smaller alpha-motoneurons that innervates type I muscle fibers are recruited first, while bigger alpha-motoneurons that activate muscle fibers IIa and IIx are recruited at higher forces (Duchateau, Semmler, & Enoka, 2006). The force-level where the largest motor units are activated correspond to the upper limit of motor unit recruitment threshold (Duchateau & Enoka, 2011). The absolute force-level where all motor units are recruited varies with the contraction velocity and type of muscle contraction. In most muscles, the upper limit of motor unit

recruitment corresponds to ~85% of maximal force during slow contractions (Duchateau et al., 2006; Kukulka & Clamann, 1981). However, the recruitment threshold decreases progressively with an increased RFD. Thus, the motor units are activated earlier in explosive contractions (Desmedt & Godaux, 1977).

When two or more motor units are activated simultaneously, the motor units are said to be firing synchronized. In which way the motor unit synchronization influences force-production is not fully understood (Cormie et al., 2011a). Studies have shown that synchronization of the motor units do not affect the muscle's maximal strength. Interestingly, at submaximal firing frequency, asynchronous discharge of action potentials is shown to result in greater force-production (Cormie et al., 2011a; Lind & Petrofsky, 1978). It has been hypothesized that synchronization has a positive influence on RFD (Komi, 1986); however, to the author's knowledge, there is no clear evidence of this.

When all motor units are activated, the further increase in muscle force production is due to an increased action potential discharge rate (Duchateau et al., 2006). For a voluntary contraction to occur an action potential needs to "travel" from the brain through a motor neuron to the muscle fiber (Enoka, 2015). This reaction involves several processes which result in calcium being released from the sarcoplasmic reticulum. Calcium then binds to tropomyosin-actin complex, causing a structural change of the actin which leads to the possibility for an interaction between the contractile filament actin and myosin (Enoka, 2015). A higher firing frequency of the action potential will allow for a greater concentration of calcium to be released from the sarcoplasmic reticulum. A higher calcium concentration will release more binding-sites on the actin, thus, allowing greater interaction between actin and myosin (Stein, Bobet, Oguztoreli, & Fryer, 1988). The muscle force production increases with increasing calcium concentration up to a specific concentration. At this concentration the number of free binding sites is at maximum (Stein et al., 1988).

During complex movements, there is an interaction between different muscles. Intermuscular coordination describes the timing and the magnitude of agonist, synergist

and antagonist muscles (Cormie et al., 2011a). Considering a movement to be as effective as possible, agonist activation should be supplemented by synergist activation and by a limited co-activation of antagonist muscles (Sale, 1988). The co-activation of antagonist's muscles depends on several factors, such as type of contraction, load, and velocity of the movement (Cormie et al., 2011a). Actions from antagonist muscles are essential for maintaining joint stabilization. However, regarding maximal power production, excessive co-activation may have a negative influence (Cormie et al., 2011a).

2.5. Muscle-tendon interaction

There is always an interaction between the muscle and the tendon in a contraction. The muscle and the tendon function therefore as one unit, called the muscle-tendon unit (MTU). The viscoelastic properties of the tendon makes it possible to uncouple muscle length changes from that of the MTU, which could enhance muscle performance (Farris & Sawicki, 2012; Ishikawa, Pakaslahti, & Komi, 2007).

The tendon can by itself influence the power production by power amplification (Roberts & Azizi, 2011). The muscle force-production and hence, the power production is limited by enzymatic processes associated with the cross-bridge cycle between actin and myosin. However, due to the structure of the tendon, the tendon does not have these limitations on power output. Energy stored during tendon stretching can be released at a faster rate, thus, increasing total power production. This mechanism can, in theory, increase the potential for the MTU to develop power during a movement (Roberts & Azizi, 2011).

The stiffness of the tendon is shown to influence the RFD (Bojsen-Moller, Magnusson, Rasmussen, Kjaer, & Aagaard, 2005). Bojsen-Moller et al. (2005) reported that there was a positive correlation between RTD and tendon stiffness. They suggested that an increased tendon stiffness is beneficial for RTD since the force is transmitted more effectively to the bones. Additionally, a decreased RFD has been observed when a compliant structure is inserted between the subject and the force transducer (Wilkie, 1949).

The electromechanical delay is the time delay between muscle activation and onset of force production (Nordez et al., 2009). The electromechanical delay is influenced by excitation-contraction coupling process (E-C) and the stiffness of the series elastic elements (Nordez et al., 2009; Norman & Komi, 1979). A stiffer tendon can, therefore, decrease the time lag since the force produced from the muscle is transmitted more effectively to the bones, which could have an influence on the early phase RFD.

2.6. Adaptations to isometric and dynamic resistance training

Resistance training is one of the most widely used training methods for enhancing athletic performance. Commonly documented adaptations after resistance training are increased muscle size (Folland & Williams, 2007), change in muscle architecture (Timmins, Shield, Williams, Lorenzen, & Opar, 2016), increased strength and rate of force development and tendon stiffness (Maffiuletti et al., 2016). Interestingly, different resistance training methods have shown to result in different neuromuscular adaptations and functional performance (Andersen, Andersen, Zebis, & Aagaard, 2010; Folland et al., 2014). In this section, I will present how isometric and dynamic resistance training could influence functional performance, changes in muscle architecture, muscle strength, and neural adaptations.

2.6.1. Functional performance

Isometric resistance training is proposed to have several advantages compared with dynamic resistance training. Isometric resistance training is often used in rehabilitation since it allows a highly controlled application of force within the pain-free joint angle (Oranchuk, Storey, Nelson, & Cronin, 2019). From a sports performance perspective, isometric contractions could allow for a greater overload as the force produced during maximal isometric contractions is higher than during dynamic contractions (Hill, 1938). However, the transferability of isometric resistance training to dynamic performance is thought to be questionable (Oranchuk et al., 2019). This may be based on the idea that the adaptation to resistance training is specific to the training modality (Behm & Sale, 1993b). Thus, it could be argued that improving performance in a dynamic movement, dynamic resistance training is superior. There are few studies which have compared

isometric and dynamic resistance training, and its influence on performance in a dynamic movement. These studies reports conflicting results. Duchateau and Hainaut (1984) reported that isometric contractions performed with a 5-second hold, and explosive dynamic contractions led to different functional improvements. In contrast, Behm and Sale (1993a) compared the effect of explosive isometric and dynamic dorsiflexion. They observed that both training modalities led to a similar increase in isokinetic dorsiflexion torque. However, the dissimilar execution, duration, and loading between the training modalities makes a direct comparison between the studies impossible. Thus, the understanding about how resistance training performed isometrically or dynamically influence performance in a dynamic movement remains unknown.

2.6.2. Changes in muscle architecture

Both isometric and dynamic resistance training have shown to lead to increased muscle size (Balshaw, Massey, Maden-Wilkinson, Tillin, & Folland, 2016; Narici et al., 1996a). Similar principles apply for isometric and dynamic resistance training regarding increase in muscle mass (Oranchuk et al., 2019). A review article from Schoenfeld et al. (2019) reported that the magnitude on the hypertrophy is mainly dependent on the training volume. There seems to be a dose-response relationship between the training volume and the magnitude of the hypertrophy (Schoenfeld, Ogborn, & Krieger, 2017).

Changes in muscle architecture are typically observed after resistance training (Timmins et al., 2016). There are not many studies that have investigated the effect of isometric resistance training on muscle architecture. Werkhausen et al. (2018) revealed that explosive isometric plantarflexion contractions led to 5% increase in gastrocnemius pennation angle and muscle thickness, without any changes in fascicle length. Furthermore, there are some studies showing that the adaptations after isometric resistance training is depending on the muscle length during the training. For instance, Noorkoiv, Nosaka, and Blazevich (2014) compared isometric resistance training at very short and long muscle length (38.1 vs. 87.5° knee flexion). They reported that the fascicle length increased only after isometric training at very short muscle length. Alegre, Ferri-Morales, Rodriguez-Casares, and Aguado (2014) investigated if isometric

training performed at 90° or 50° knee flexion resulted in different adaptations. They reported that the vastus lateralis pennation angle did only increase after isometric resistance training at long muscle length.

A review article by Timmins et al. (2016) revealed that most intervention studies observe an increased pennation angle after dynamic resistance training. Interestingly, an increased fascicle length is more often observed after eccentric resistance training (Timmins et al., 2016). The understanding about which factors affect the changes in muscle architecture is not fully understood. It has been speculated if the changes in muscle architecture are depending on the force and velocity characteristics of the movement (Timmins et al., 2016). One study by Blazevich, Gill, Bronks, and Newton (2003) reported that explosive high-velocity sprint/jump training led to decreased pennation angle and increased fascicle length. In contrast, slower-velocity resistance training resulted in an increased pennation angle without any changes in fascicle length (Blazevich et al., 2003).

2.6.3. Increased muscle strength

Both isometric and dynamic resistance training has shown to result in increased muscle strength (Folland, Hawker, Leach, Little, & Jones, 2005; Graves, Pollock, Jones, Colvin, & Leggett, 1989; Weir, Housh, Weir, & Johnson, 1995). The increased strength found after resistance training is thought to be related to the increase in muscle size. However, a disproportionate increase in muscle strength and size is often reported (Folland & Williams, 2007). Thus, the increase in muscle strength is thought to be due to both neural and muscular adaptations (Folland & Williams, 2007). There are some studies which have compared the increase in strength after resistance training performed with different ROM. Jones and Rutherford (1987) are one of few studies that used similar relative loads to compare isometric, concentric and eccentric contractions. Interestingly, they reported that isometric resistance training led to a more significant increase in isometric strength measured at the isometric training angle. There was no significant difference in increased muscle size in either of the training modalities. Unfortunately, muscle strength was not measured at any other angles. It is possible that isometric strength training led to neural adaptations which is specific to the training

angle, and it is unknown to which degree the increase in strength reported after isometric resistance training is transferable to other muscle lengths (Kitai & Sale, 1989; Lindh, 1979; Thepaut-Mathieu et al., 1988; Weir et al., 1995). In contrast, dynamic resistance training results in increased strength throughout the training ROM (Graves, Pollock, Jones, Colvin, & Leggett, 1989).

2.6.4. Neural adaptations

Resistance training typically leads to neural adaptations which could improve maximal force production and RFD (Sale, 1988). It has been shown that isometric and dynamic resistance training leads to neural adaptations (Balso & Cafarelli, 2007; Tillin & Folland, 2014). Typical adaptations reported is increased muscle activation at the onset of the contraction (Maffiuletti et al., 2016), which will result in an increased early phase RFD (de Ruyter, Kooistra, Paalman, & de Haan, 2004). However, it is speculated that the neural adaptations are specific to the execution of the contraction, irrespectively to the ROM or load (Behm & Sale, 1993a). For instance, Balshaw et al. (2016) observed that explosive isometric contractions led to different neural adaptations compared with isometric sustained contractions. The explosive execution of the contraction led to a greater EMG activity during the first 0-150 ms after force onset. Similar results have been reported after dynamic explosive and maximal force resistance training (Tillin & Folland, 2014). Thus, the increased muscle activation at the initial part of the contractions found after resistance training is dependent on the execution and not the ROM.

2.7. Summary

In the above section, the factors which influence muscular power production were presented. Mechanical properties of the muscle dictate the muscular power production. The mechanical properties are influenced by several factors including muscle morphology, neural factors and tendon properties.

The muscle morphology includes muscle fiber type, muscle CSA, pennation angle and fascicle length. The force and power production at higher velocities are highly

influenced by muscle fiber type and muscle architecture. As long as all other factors are equal, a muscle with greater CSA will produce higher force at all velocities. However, bigger muscle is often related to a greater pennation angle which is speculated to be beneficial for force-production at slow velocities but has a negative influence on the force production at higher-velocities. Furthermore, longer fascicle is speculated to be beneficial for explosive force production due to a higher maximal shortening velocity.

The nervous system plays an important role for muscle force-production by modulation of motor unit recruitment and action potential discharge rate.

The viscoelastic properties of the tendon make it possible to uncouple muscle length changes from that of the muscle-tendon unit, which could enhance the muscle performance.

Resistance training has shown to result in muscular and neural adaptations which are shown to influence functional performance. The adaptations reported after resistance training is shown to be specific to the training modality. On the other hand, some studies have shown that emphasizing on developing high RFD will result in similar adaptations regardless of the joint operating range or the velocity of the movement. Thus, the conflicting results between the studies may be due to the dissimilar execution, duration and loading between the training modalities, which makes a direct comparison of the training modalities impossible.

3. Method

3.1. Study design

To compare the effects of explosive resistance-training performed with very short or full ROM, the participants completed a 10-week resistance training program. The training was performed unilaterally, with each leg assigned to explosive very short (~10°) or full ROM contractions. Half of the participants trained their dominant leg as very short ROM, and the other half trained their dominant leg as full ROM. The effect of the intervention program was evaluated through pre- and post-tests including; ultrasound measurement of vastus lateralis, voluntary and electrical induced RTD of knee-extensor muscles, and isokinetic knee extension torque. Also, peak power and force were measured during full ROM leg press (80-180° knee angle). The participants gave their written informed consent before the start of the study.

3.2. Subjects

A total of 16 males and females were recruited via social media and posters on the basis that they were healthy, young (<40 years old), injury free and had completed ≥ 1 leg strength session each week for the last 6 months. The participants were instructed to not perform any other types of resistance training on the lower limbs during the training period. To be sure that the data reflected the effect of the intervention, we included a criterion concerning the adherence of the intervention period. The participants had to complete at least 90% of the intervention training sessions. All 16 participants managed this requirement by completing a minimum of 27 of 30 training sessions. One participant was excluded in the analyzing process due to sickness prior to the post-test.

Table 1. Participant details pre and post-training intervention. Numbers are mean \pm SD.

	All (n=15)	Females (n=5)	Males (n=10)
Age (y)	25 \pm 4	27 \pm 3	24 \pm 4
Height (cm)	176 \pm 10	163 \pm 2	182 \pm 6
Body mass pre (kg)	72 \pm 9	62 \pm 4	76 \pm 7
Body mass post (kg)	73 \pm 9	62 \pm 3	78 \pm 7

3.3. Experimental procedures

For pre- and post-testing, two test sessions were completed with at least 48 hours between test sessions. The first test session included; ultrasound measurement of vastus lateralis, voluntary and electrical induced RTD of knee-extensor muscles, and isokinetic knee extension torque. On a separate day, the leg press test was completed. All participants completed one familiarization-session before the pre-test.

3.3.1. Ultrasonography

B-mode ultrasound measurement was performed on vastus lateralis muscle on both legs of all participants, using a linear array transducer (50mm, 5-12MhZ, HD11XE, Philips, Bothell, Washington, USA). The ultrasound device used during the pre-test was damaged and out of order for the post-test. For this reason, another ultrasound device (HL9.0/60/128Z-2, LS 128 Telemed, Vilnius, Lithuania) had to be used for this time point. A calibration procedure based on phantom scanning ensured a consistent scaling with both apparatuses. The measurement was performed while the participant was lying supine and instructed to be fully relaxed. The ultrasound pictures were taken at the thickest part of vastus lateralis at 60% of the distance from the greater trochanter to the lateral epicondyle on the femur. The leg position of the participants was standardized and fixed in anatomical position (foot aligned with the sagittal plane) during scanning.

Analysis: Ultrasound images were analyzed using a custom-made script of semi-automated segmentation in Fiji (version 2.0.0, USA). Muscle thickness was measured as the mean distance between aponeuroses. The dominant orientations of fascicles and aponeuroses were measured using a script based on the evaluation of the gradient structure tensor in a local neighborhood and used to compute the pennation angle. Fascicle length was calculated as a straight line aligned with the dominant fascicle orientation, between the superficial and deeper aponeuroses. Pilot testing using this method showed that it did not induce any variability in multiple measurements and that it did not induce any systematic bias (comparable values) when compared to manual analysis. 2D ultrasound is widely used for measuring muscle architecture, and studies have concluded that 2D ultrasound is a valid and reliable method for measuring muscle

architecture across a broad range of experimental conditions (Kwah, Pinto, Diong, & Herbert, 2013). The coefficient of variance (CV) for ultrasound measurements are shown to be 2.3-9.8% and 2.1-13.5% for respectively fascicle length and pennation angle, and an ICC of 0.81 for muscle thickness (Giles, Webster, McClelland, & Cook, 2015; Kwah et al., 2013).

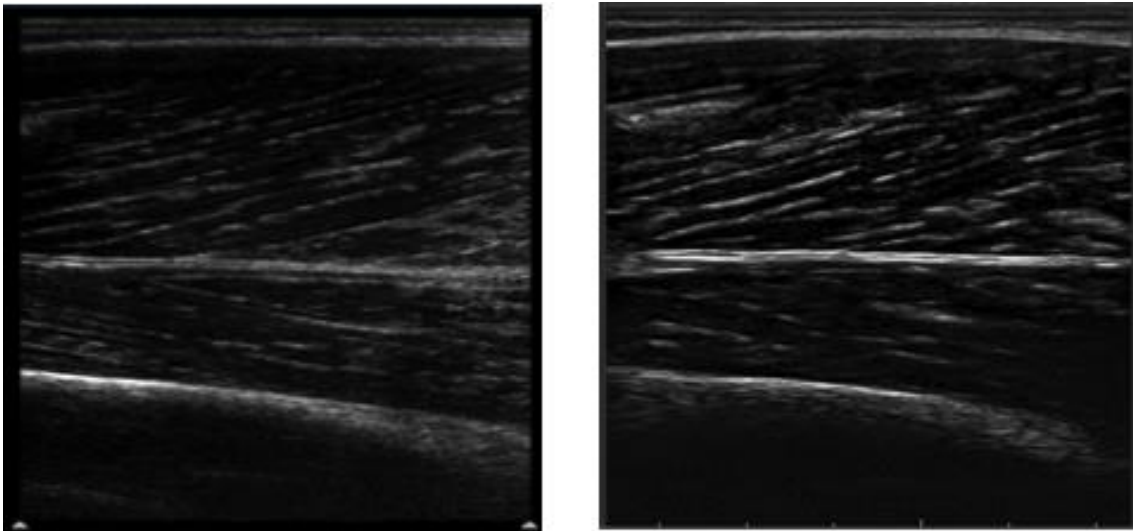


Figure 2. *Pre (left) and post (right) ultrasound pictures of m. vastus lateralis from one participant with the deep and superficial aponeurosis (clear white lines).*

3.3.2. Voluntary isometric torque

After the ultrasound measurements, the participants completed a standardized 10 min warm-up on an ergometer cycle before the strength tests. The isometric RTD was tested on both legs (unilateral) seated in a modified knee extension machine (GYM 2000 Gym Equipment, Geithus, Norway) with a 90° knee angle. Identical pre- to post- training positioning of the seat and the lever arm was employed for each subject. The force-production was measured with a force sensor (HBM U2A 200kg, Darmstadt, Germany). A specific warm-up protocol was performed before the RTD testing consisting of 10, 6 and 4 submaximal repetitions, respectively. The participants then performed one maximal voluntary contraction (MVC). The RTD test-protocol consisted of 2 sets of 5 repetitions with an inter-repetition rest period of approximately 5 seconds. The participants were instructed to extend their knee as fast as possible until the force was

approximately 80% of MVC. Online visual feedback of the strain gauge signal was provided to the subjects on a computer screen.

Analysis. The analysis was performed in MATLAB (version R2018b, The MathWorks, USA). The force signal was sampled at a frequency of 5000 Hz. The signal was smoothed with a bidirectional fourth order 20 Hz low pass filter. Subsequently, the signal was converted to newtons and multiplied by the individual lever arm to calculate the knee extension torque. The lever arm was calculated as the distance from the greater trochanter to the lateral epicondyle on the femur. The onset of torque development was defined as the point where the torque exceeded 3 Nm. Repetitions with pre-activation and/or a countermovement was excluded. Electromyography (EMG) measured from the vastus lateralis was used to determine pre-activation. If the EMG signal exceeded 3 SD from baseline value at the time interval 500-100 ms before onset torque, the contraction was excluded due to pre-tension. Furthermore, all repetitions were visually overlooked, and if the torque signal just before the onset of torque was below baseline values, the repetition was excluded due to a countermovement. The average values from the three best contractions with the highest torque at 50 ms was used to calculate torque at 50, 100 and 150 ms. One participant was excluded after the analysis due to an insufficient number of valid contractions. Thus, the results from the voluntary isometric contractions are based on 15 participants. Our analysis did show that CV for torque at 50, 100 and 150 ms was 9.0, 8.8, and 6.3% respectively.

3.3.3. Surface electromyography (EMG)

EMG activity of the vastus lateralis and vastus medialis muscle was measured during the voluntary isometric rate of torque development test. After shaving, abrading, and cleaning of the skin with 70% ethanol, the electrodes (Ambu Neuroline 720 7200-S/25, Penang, Malaysia) were placed in a bipolar configuration, parallel to the muscle-fiber direction, with an interelectrode distance of 20mm. Reference electrodes were placed on the left and right side of the patella. Electrode sites were marked on a transparent sheet to ensure identical placement of the electrodes during pre-and post-testing.

Analysis. The analysis was performed in MATLAB (version R2018b, The MathWorks, USA). The EMG signal was sampled at a frequency of 5000 Hz and was rectified and smoothed with a bandpass filter with a cutoff of 10 and 500Hz. The EMG was intended to be used for measuring the electromechanical delay. Unfortunately, there was some methodological challenges in automatically defining the onset of EMG activity. Thus, EMG was only used to determine pre-activation during voluntary isometric torque (see section 3.3.2 voluntary isometric torque).

3.3.4. Electrically evoked torque

The experimental setup was identical as used during voluntary isometric contractions. Electrically evoked contractile properties of the quadriceps were determined when the subjects were at rest. One surface stimulation electrode (Veinoplus, GMDN code: 34374, Paris, France) was placed over the proximal part of vastus lateralis, and one stimulation electrode 2-3 cm directedly over the patella (see figure 1.0). Electrical stimulation consisting of single square wave pulses of 0.2 ms. duration delivered by a direct current stimulator (Digitimer Electronics, model DS7, Hertfordshire UK). Stepwise increments in the current were delivered, until no further increase in twitch amplitude was seen. Then five maximal twitches with an inter-repetition rest period of about 4-5 seconds were given.



Figure 3. *Experimental setup for the electrical evoked RTD test.*

Analysis: The analyses were performed in MATLAB (version R2018b, The MathWorks, USA). The signal was smoothed with a bidirectional fourth order 20Hz low pass filter. The force signal was converted to Newton and multiplied with the lever to obtain the knee joint torque. The onset of torque development was defined as the point where the torque exceeded 3 Nm. Contractions were excluded due to pre-tension if the delay between stimulation artifacts and the onset

of torque was $< 0,01$ seconds. The average values from the three best contractions with the highest torque at 50 ms. was used in the analysis. Following twitch characteristics was determined: (1) peak torque (2) peak torque at 50ms (3) delay between stimulation artifacts and onset torque. Electrical evoked contractions are shown to have a higher reliability than voluntary contractions when testing common strength test variables such as peak force, time to peak torque, the rate of torque development. The CV for peak force and force at 50ms. is shown to be respectively 7.6 and 8.3% (Jenkins, Palmer, & Cramer, 2014).

3.3.5. Isokinetic knee-extensor torque

Maximal concentric knee-extensor torque was measured using an isokinetic dynamometer (Humac NORM 2008, Computer Sports Medicine Incorporated [CSMi], Stoughton, MA). A standard protocol for the position was used: The participant sat upright in a chair at an 85° back-angle, supported by chest, hip, and thigh straps, with the back of the knees positioned at the edge of the seat. The axis of rotation of the dynamometer lever arm was visually aligned to the lateral femoral condyle. The lower leg was attached distally to the lever arm of the dynamometer at a position just above the medial malleolus. Identical pre- to post training positioning of the seat and dynamometer lever arm was employed for each subject. Torque measurements were gravity corrected, and the reference gravity torque was determined at 0° knee angle (fully extended). Concentric knee extension torque was measured from 90° to 0° knee flexion, allowing a standardized 90° ROM. The concentric knee-extensor torque was measured at 30, 60, 180 and 300°s^{-1} . Each velocity consisted of three maximum voluntary contractions separated by 2-minute recovery periods between the first three velocities (30, 60, 180°s^{-1}) and 1-minute recovery period before the fastest contraction. All participants had the same order of the velocities, from slowest to fastest.

Analysis: The analysis was performed in MATLAB (version R2018b, The MathWorks, USA). The torque was sampled at a frequency of 100 Hz. The torque data from the last 30° and the first 10° of the ROM was removed due to an increase in torque which was non-physiological. The repetition with the highest torque value at each velocity was used for calculating peak torque, and average values from all three repetitions at each

velocity were used for calculating the angle at peak torque. Work was calculated from integration of the torque-angle relationship. The work production was measured from 80° to 35° knee angle, additionally, the ROM was divided into three parts (80-65°, 65-50° and 50-35° knee angle). Isokinetic strength tests are often used as a reference standard for other strength test assessments and are considered a valid and reliable instrument for measuring muscle strength. Our analysis showed that CV for peak torque at 30, 60, 180 and 300°s⁻¹. was respectively 4.4, 4.0, 5.5 and 3.5%.

3.3.6. Leg press power test

The Keiser leg press (Air 300 leg press) was used to measure unilateral power production in the leg extensor apparatus. A standard protocol for positioning was used: The knee angle was 80° for all the participants, and the hip angle varied between 65° and 70°. The small variation of the hip angle was due to the machine adjustability. The participants performed a 10 min warm-up protocol on an ergometer cycle before a specific warm-up protocol in the Keiser machine consisting of 10, 6 and 4 repetitions, respectively. The participants then performed a 1RM test unilaterally on both legs. After approximately 3 minutes rest-period, the participants performed the Keiser 10-repetitions power test. The test is characterized by a gradual increase in load with a gradually increase inter-repetition rest period. The load at the 10th repetition was equivalent to 95% of 1RM, and the loads used during the post-test was identical as during the pre-test. The participant was instructed to push as hard and fast as possible during all repetitions.

Analysis: The data was imported to the Norwegian Olympic and Paralympic Sports Centres Keiser database. A custom-made web software analyzed the data. Peak power was automatically calculated in the software. Peak power was calculated as the largest product of force and velocity based on the linear force-velocity regression line; i.e., the top of the power parable. The Keiser power test was used in this study to investigate if the training modalities led to different adaptations in a dynamic multi-joint movement. To the authors knowledge, there have been no published studies investigating the validity and reliability of the Keiser power test. Between-tests reliability data performed in our lab showed CVs of 3% for both peak power and peak force.

3.4. Training

The training consisted of three sessions each week for 10 weeks, and every training session was supervised. The participants trained their knee extensor muscles unilaterally in a standard leg press machine (Panatta leg press 45°, Apiro, Italy). Starting leg joint configuration was set at 90° of knee flexion and 80° of hip flexion. Ropes and chains were used for adjusting the starting and end-point angular positions. The order of the training side (very short or full ROM) within each training session was altered each session. The training sessions were performed with 4, 6 or 8 repetitions. The number of working sets increased in a non-linear fashion during the intervention period (see figure 2.0). Prior to the first training session, the 4, 6, and 8 repetition maximum (RM) was established in full ROM. The full ROM RM-loads were used as the initial training loads for both short - and full-ROM legs. During the intervention period, the loads were adjusting weekly by using the RPE score (1-10). The participants rated each leg every session and if the participants rated the effort below 8, the weight was increased by 5kg the next week. Thus, the weight lifted for each leg did increase independently. The participants were instructed to perform every repetition as explosively as possible and were verbally encouraged. In the eccentric part of the movement, the participants were instructed to let the load fall back without opposing any resistance. A rest period of about three seconds was included between repetitions.

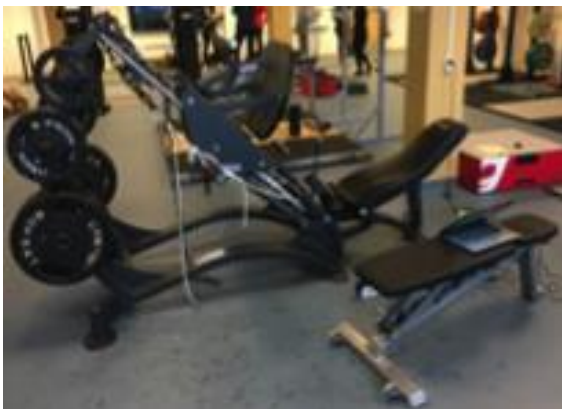


Figure 4. Leg press machine used for the training.

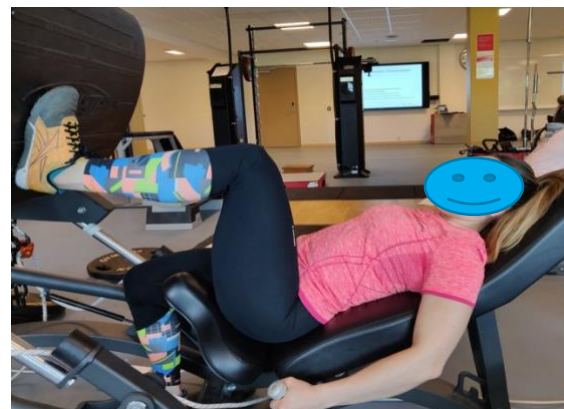


Figure 5. Starting hip and knee joint position.

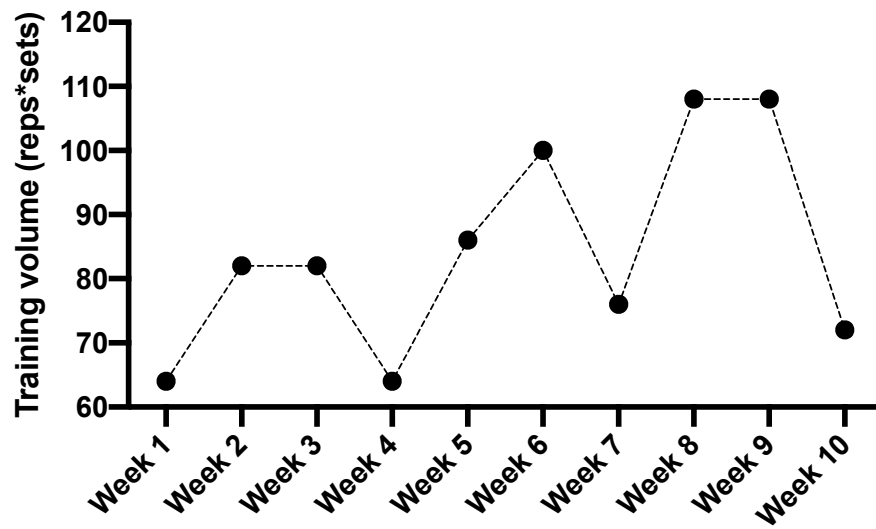


Figure 6. *Graphic presentation of the training volume beyond the training period.*

3.5. Statistics

All variables were checked for normal distribution visually and statistically with the D`Agostino & Pearsons test. A 2-way ANOVA followed by Sidaks multiple comparisons test were performed using GraphPad Prism version 8.0.2 (GraphPad Software Inc., San Diego, CA, USA) to determine main time effects and interaction effects between legs. Data from the pre-and post-testing are presented as mean \pm SD, and the level of significance was set to $P < 0.05$. The number of participants does vary in some of the test due to loss of some data.

4. Results

There was no significant difference between the training modalities in any of the measured parameters at baseline.

4.1. Leg press

Both training modalities led to increased leg press 1RM and mechanical power production at all relative loads tested (Figure 7 & Table 2).

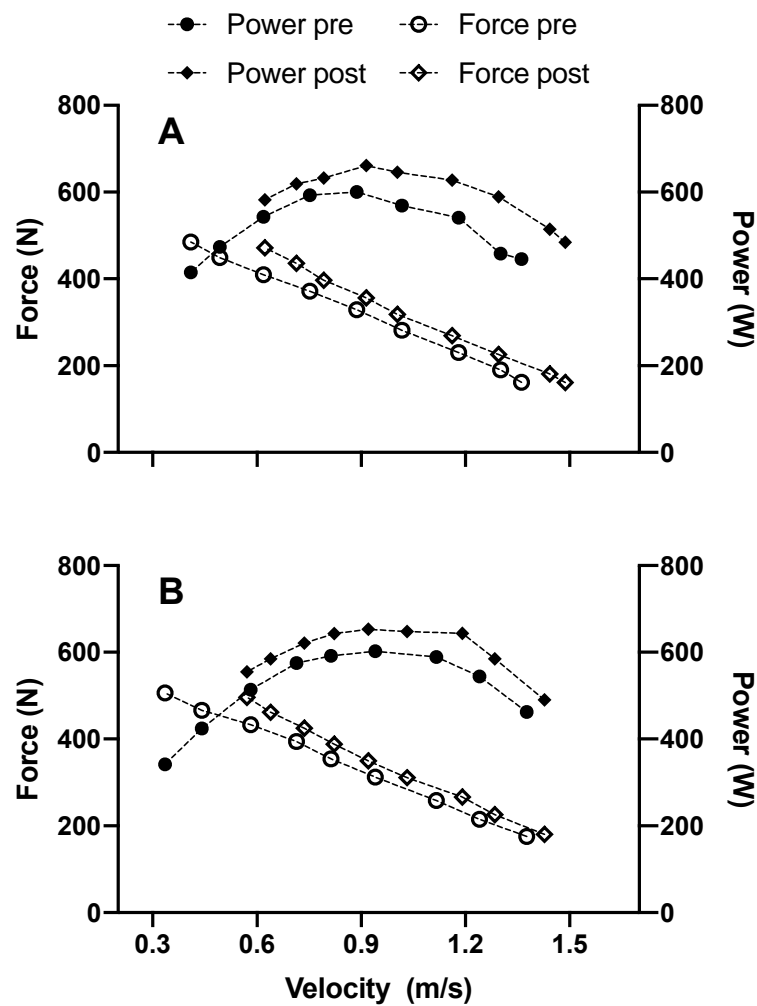


Figure 7. Force-velocity and power-velocity relationship pre- and post-training period for A = very short ROM and B = full ROM. Similar loads were used for the pre- and post-tests. Error bars and significant markers are removed for clarity. n = 15

Both training modalities led to a significant increase in 1RM and peak power. There was no significant interaction effect in any of the measured parameters from the leg press tests, which indicate that both training modalities led to a similar response.

Table 2. 1RM and peak power measured in the leg press at pre- and post-training period.

Variable	n	Very short ROM		Full ROM		P-main	P-interaction
		Pre	Post	Pre	Post		
1 RM leg press (kg)	15	133 ± 39	168 ± 41	132 ± 38	169 ± 41	<0.01*	0.52
Peak power (W)	15	293 ± 88	329 ± 92	301 ± 95	332 ± 86	<0.01*	0.54

n = number of subjects, * Significant main effect P<0.05

4.2. Isokinetic knee extension

4.2.1. Torque-velocity relationship

Both training modalities show a similar high-velocity specific training response (Figure 8). Peak torque at 180°s⁻¹ increased by 5 ± 5.6% and 5.5 ± 9.1%, respectively, for very short and full ROM sides. Peak torque at 300°s⁻¹ increased by 4.2 ± 6.2% and 6.3 ± 9.8% for respectively very short and full ROM. There were no significant changes in peak torque at 30°s⁻¹ and 60°s⁻¹ for neither of the training modalities.

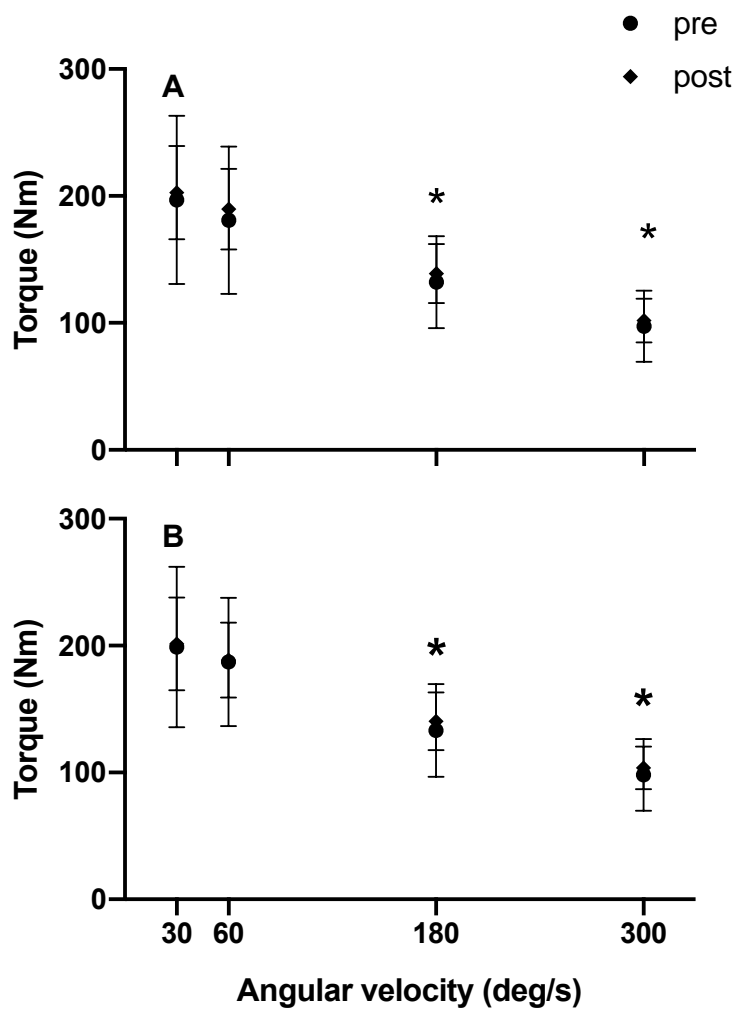


Figure 8. Torque-velocity relationship before and after the training period for A = very short ROM and B = full ROM. * Significant main effect $P < 0.05$

4.2.2. Work production

Both training modalities resulted in a significant difference in the total amount of work produced at 180°s^{-1} , and 300°s^{-1} (Figure 9 & Table 3). To determine in which part of the ROM the work production increased, we divided the ROM into three sections (35-50, 50-65 and 65- 80°), full extended knee = 0° . The analysis showed that work production increased significantly throughout the entire ROM for both training modalities. An interaction effect at $80-65^{\circ}$ and $65-50^{\circ}$ knee angle was observed at 300°s^{-1} , full ROM had relatively greater improvement compared to very short ROM.

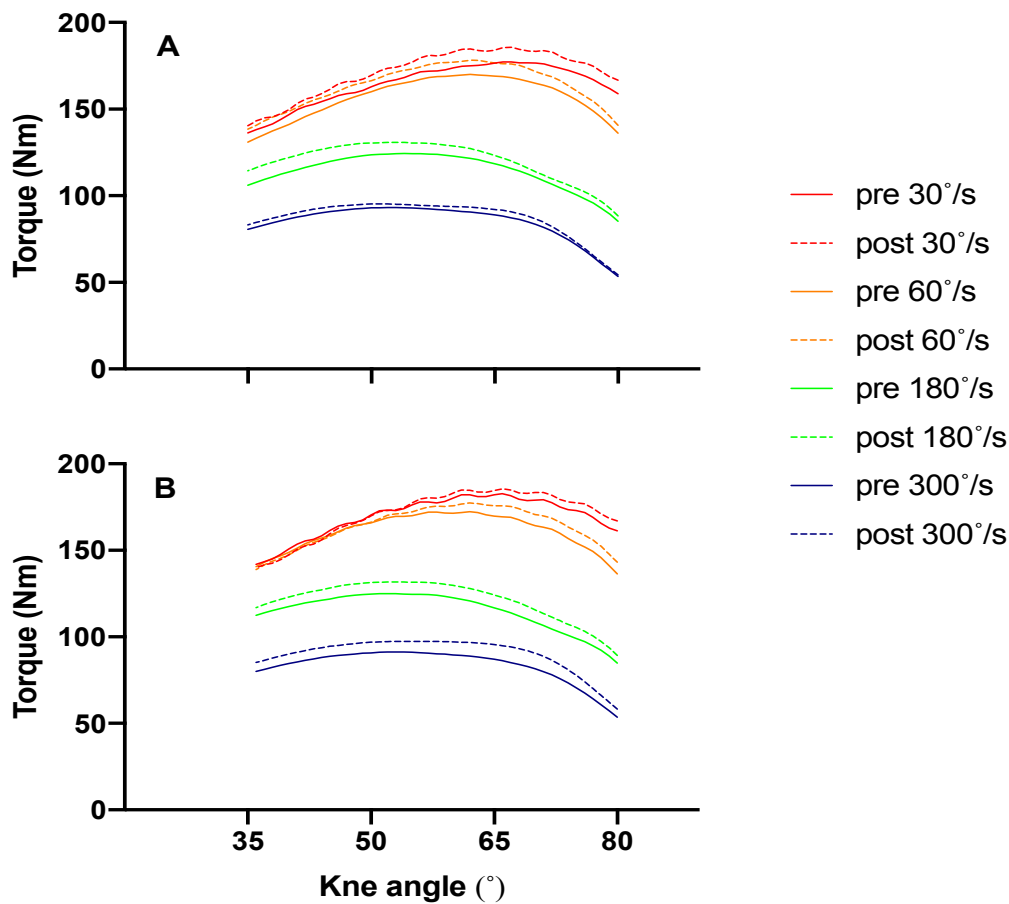


Figure 9. Torque-angle relationship before and after the training period for A= very short ROM and B= full ROM. The error bars are removed for clarity.

Table 3. Pre- and post- values of the total work produced over the full ROM and the work produced at the different part of the ROM at the angular velocities of 30°s^{-1} , 60°s^{-1} , 180°s^{-1} , and 300°s^{-1} . Full extended knee = 0° .

Variable	Knee angle ($^{\circ}$)	Very short ROM		Full ROM		P-main	P-interaction
		Pre (J)	Post (J)	Pre (J)	Post (J)		
Work at 30°s^{-1}							
	80-35	9384 \pm 2988	9789 \pm 3117	9636 \pm 3070	9717 \pm 2938	0.30	0.14
	80-65	2581 \pm 923	2692 \pm 914	2621 \pm 866	2687 \pm 854	0.28	0.36
	65-50	2569 \pm 859	2692 \pm 883	2663 \pm 873	2689 \pm 855	0.28	0.14
	50-35	2124 \pm 667	2195 \pm 700	2191 \pm 715	2164 \pm 651	0.70	0.19
Work at 60°s^{-1}							
	80-35	8887 \pm 2592	9299 \pm 2720	9106 \pm 2597	9257 \pm 2645	0.10	0.19
	80-65	2373 \pm 790	2468 \pm 751	2374 \pm 717	2472 \pm 733	0.12	0.91
	65-50	2506 \pm 785	2618 \pm 789	2558 \pm 739	2607 \pm 770	0.15	0.21
	50-35	2063 \pm 571	2165 \pm 648	2167 \pm 632	2154 \pm 619	0.27	0.14
Work at 180°s^{-1}							
	80-35	6482 \pm 1733	6845 \pm 1960	6560 \pm 1708	6897 \pm 1808	0.01 *	0.86
	80-65	1570 \pm 468	1625 \pm 498	1547 \pm 431	1646 \pm 460	0.01 *	0.10
	65-50	1844 \pm 514	1934 \pm 577	1844 \pm 492	1949 \pm 545	0.01 *	0.69
	50-35	1638 \pm 410	1750 \pm 488	1678 \pm 434	1760 \pm 452	0.02 *	0.55
Work at 300°s^{-1}							
	80-35	4715 \pm 1317	4872 \pm 1355	4651 \pm 1344	5007 \pm 1301	0.01 *	0.07
	80-65	1135 \pm 368	1168 \pm 370	1117 \pm 392	1232 \pm 369	0.02 *	0.01 *#
	65-50	1378 \pm 396	1411 \pm 388	1350 \pm 397	1455 \pm 392	0.01 *	0.04 *#
	50-35	1242 \pm 342	1279 \pm 356	1213 \pm 340	1292 \pm 331	0.03 *	0.13

* Significant main effect $P < 0.05$, *# Significant interaction effect $P < 0.05$

4.2.3. Angle at peak torque

Neither of the training modalities led to any changes in angle at peak torque at the post-test (Table 4).

Table 4. *Knee-angle at peak torque at angular velocities 30°s^{-1} , 60°s^{-1} , 180°s^{-1} and 300°s^{-1} from pre- and post-training period. Fully extended knee = 0° .*

Variable	n	Very short ROM		Full ROM		P-main	P-interaction
		Pre ($^{\circ}$)	Post ($^{\circ}$)	Pre ($^{\circ}$)	Post ($^{\circ}$)		
Angle at peak torque 30°s^{-1}	15	59 ± 9	61 ± 8	61 ± 7	62 ± 6	0.33	0.75
Angle at peak torque 60°s^{-1}	15	58 ± 7	59 ± 6	57 ± 6	60 ± 6	0.11	0.19
Angle at peak torque 180°s^{-1}	15	53 ± 5	52 ± 5	52 ± 6	52 ± 5	0.55	0.40
Angle at peak torque 300°s^{-1}	15	53 ± 6	54 ± 7	55 ± 7	55 ± 7	0.62	0.61

n = number of subjects

4.3. Isometric rate of torque development

4.3.1. Voluntary torque development

Both training modalities led to a significant increase in torque at 50, 100, and 150 ms after torque onset (Figure 10). Short ROM increased torque by $50.3 \pm 50\%$, $42.1 \pm 24.1\%$ and $39.8 \pm 23.5\%$ at respectively 50 ms, 100 ms and 150 ms. Full ROM increased torque with $37.4 \pm 32.8\%$, $30.1 \pm 17.7\%$ and $29.6 \pm 17.0\%$ at respectively 50 ms, 100 ms and 150 ms. There was a significant interaction between training modalities at 150 ms ($P < 0.04$).

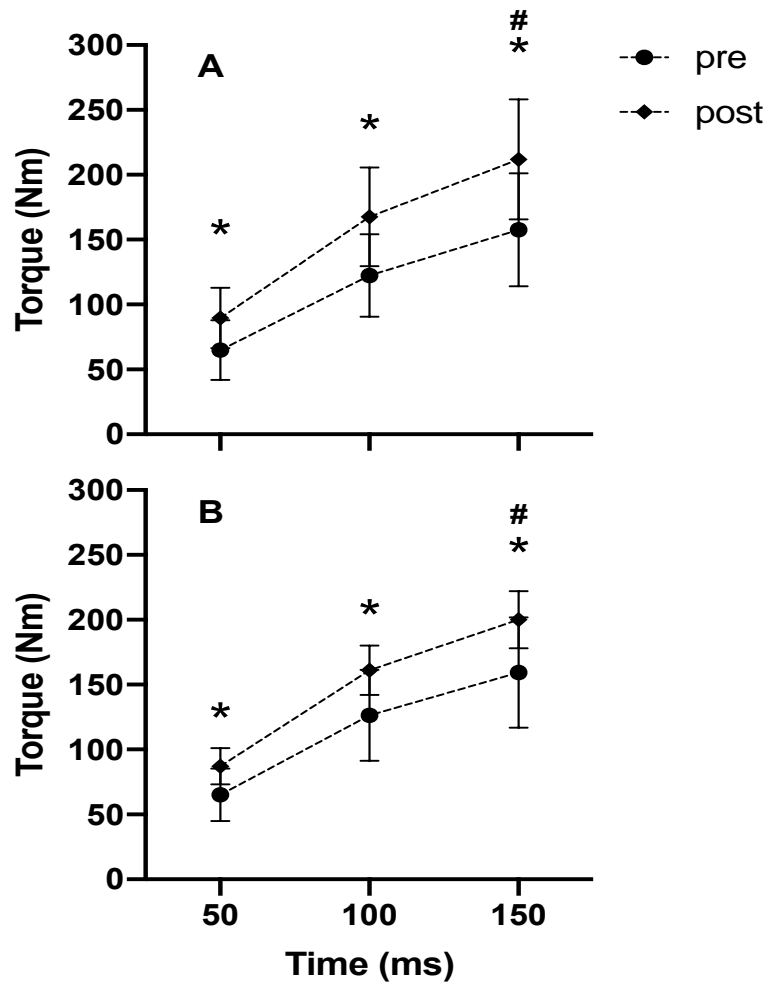


Figure 10. Torque-time curve before and after the training period for A = very short ROM and B = full ROM. n=14. * Significant main effect $P < 0.05$, *# Significant interaction effect $P < 0.05$

4.3.2. Electrical induced torque development

Both training modalities increased peak torque and torque at 50 ms after the training period (Table 5). Very short ROM increased torque at 50 ms and peak torque with respectively $24.0 \pm 20.9\%$ and $31.3 \pm 22.3\%$. Full ROM increased torque at 50 ms and peak torque with respectively $36.1 \pm 17.3\%$ and $37.1 \pm 18.6\%$. There was a significant reduction in the time lag between stimulation artifacts and onset torque after the training period for both training modalities. The reduction corresponded to $3.3 \pm 3.6\%$ and $3.9 \pm 7.1\%$ for respectively very short and full ROM. There was no significant interaction between the training modalities, which indicate a similar improvement in isometric evoked knee extension torque.

Table 5. Peak torque and torque at 50 ms for both training modalities pre- and post-training period.

Variable	n	Very short ROM		Full ROM		P-main	P-interaction
		Pre	Post	Pre	Post		
Peak torque (Nm)	15	42 ± 14	55 ± 20	41 ± 13	56 ± 17	<0.001*	0.47
Torque at 50 ms (Nm)	15	40 ± 13	49 ± 15	39 ± 12	52 ± 14	<0.001*	0.07
Delay between stimulation artifacts and onset torque (ms)	15	34 ± 4	33 ± 4	35 ± 6	33 ± 5	0.01*	0.46

* Significant main effect P<0.05

4.4. Muscle architecture

There was no significant increase in muscle thickness after the training period for neither of the training modalities. Pennation angle decreased by $12.1 \pm 11\%$ and $9.3 \pm 11.4\%$ for respectively very short and full ROM. Fascicle length increased with $13.2 \pm 11.6\%$ and $9.6 \pm 14.1\%$ for respectively very short and full ROM (Table 6). There was no significant interaction in any of the architecture measurements between the training groups.

Table 6. Muscle thickness, pennation angle and fascicle length for both training modalities pre- and post-intervention period.

Variable	n	Very short ROM		Full ROM		P-main	P-interaction
		Pre	Post	Pre	Post		
Muscle thickness (mm)	14	25.5 ± 3.5	25.2 ± 2.9	26.1 ± 3.8	25.5 ± 3.6	0.07	0.63
Pennation angle (°)	14	19.9 ± 3.1	17.3 ± 2.3	18.7 ± 2.2	16.8 ± 1.8	<0.01*	0.38
Fascicle length (mm)	14	79.8 ± 12.7	89.7 ± 12.1	84.5 ± 12.6	91.7 ± 12.4	<0.01*	0.45

* Significant main effect P<0.05

5. Discussion

The present study demonstrated that explosive resistance training of the knee-extensors leads to very similar adaptations irrespectively of operating ROM. Both training modalities led to an increased leg press peak power at various loads configurations. Additionally, the increase in (isokinetic) knee extension torque and mechanical work was velocity specific, with a significant improvement only at higher velocities for both training modalities. One of the few adaptations that differed between the training modalities was that full ROM resistance training led to a significantly greater improvement in isokinetic work production in the first part of the ROM. Consistent with the results from the functional tests, both training modalities led to an increased voluntary and electrically evoked RTD measured in isometric knee extensions. Interestingly, the very short ROM group displayed a significantly greater improvement in isometric knee extension torque at 150 ms after torque onset. The improved RTD is ascribed to neural and muscular adaptations improving rapid force production in the initial part of the movement. Hence, owing to a muscle work increases equivalent to that produced during full ROM movements, explosive training with very short ROM contractions seems to be just as effective as full ROM dynamic contractions for improving power, torque and work production in high-velocity movements.

To the author's best knowledge, this is one of few resistance training studies where the load was matched, and both training modalities performed explosive contractions. Unlike other studies, the present study had only ROM as an independent variable. Previously, studies have investigated if training with different ROM influences performance in a dynamic full ROM movement differently, however, results are conflicting. Some studies report that training with different ROM leads to different functional improvement, while other reports that differences in training ROM does not influence the adaptations (Behm & Sale, 1993a; Duchateau & Hainaut, 1984). There are some methodological issues regarding these studies which have likely influenced the results. For instance, in the study by Duchateau and Hainaut (1984) the isometric training was performed with a 5-second ramp contraction, while the dynamic training was performed explosively. Thus, the dissimilar execution and loading between the

training modalities makes a direct comparison impossible. A previous study has reported that explosive and non-explosive isometric contractions lead to different adaptations specific to the training modality (Tillin & Folland, 2014). Additionally, similar results have been observed after dynamic resistance training (Fielding et al., 2002). Thus, it is likely that the dissimilar execution of the contractions may have influenced the results.

5.1. Change in functional performance

The functional changes found in both groups, in particular at higher velocities are consistent with our hypothesis and are attributed to the specificity principle of explosive training. The results from the functional performance tests show that both training modalities led to similar improvement. A possible explanation for the similar response between the two training modalities found in the present study, may be due to the muscle behavior during the training. Although the ROM was limited in the very short ROM, a substantial shortening of the muscle fibers is likely to occur since the force exerted by the muscle will stretch the compliant tendon before it is transmitted to the bone to create movement (Ito, Kawakami, Ichinose, Fukashiro, & Fukunaga, 1998). Additionally, studies that have analyzed muscle behavior during explosive movement have shown that the shortening of the muscle is mostly limited to the initial part of the movement (Kurokawa et al., 2001; Nikolaidou et al., 2017). Since most of the work is being performed in the first half of full ROM movements, the similar changes seen with both training modes are attributable to similar effects of the training.

The results from the leg press show that both training modalities led to a similar increase in power at different load configurations and 1RM. Interestingly, both training modalities led to increased power production at high-and low-loads, despite that the training was performed with high load. Similar results have been shown by Moss, Refsnes, Abildgaard, Nicolaysen, and Jensen (1997), who reported that explosive high-load resistance training led to increased power production at high-and low-loads. However, Duchateau and Hainaut (1984) showed that high-load resistance training led to a specific increase in power production at high loads, with little transfer to lighter

loads. The conflicting results between the studies may be due to the execution of the contraction. In the present study and the study by Moss et al. (1997), all contractions were performed as explosively as possible. However, in the study by Duchateau and Hainaut (1984) the isometric contractions were performed with a 5-second duration without any emphasis on developing high RFD. The explosive execution of the contraction has shown to have a significant influence on the adaptation (Balshaw et al., 2016; Fielding et al., 2002). Fielding et al. (2002) reported that explosive training at 70% of 1RM led to a significantly greater increase in peak power than slow resistance training at 70% of 1RM. Additionally, Behm and Sale (1993a) reported that explosive isometric and dynamic contractions led to similar improvement in high-velocity dorsiflexion torque. They suggested that explosive contractions regardless of the movement type or velocity will lead to an increased RFD and similar adaptations in the motor recruitment pattern, which will lead to increased force-production at higher-velocities. The explosive execution of the contractions seems to be a key stimulus for improving high-velocity performance, which could explain why very short ROM and full ROM resistance training led to similar high-velocity improvement in leg press and isokinetic knee extensions.

To exclude the potential argument that the high-velocity adaptation found in the leg press only applies specifically to the training movement, functional performance was also assessed in isokinetic knee extensions. The results from the isokinetic knee extension test showed that both training modalities led to a similar high-velocity improvement in torque and work production. The high-velocity improvement found in the leg press and isokinetic knee extensions is thought to be associated with the increase in RTD (Duchateau & Hainaut, 1984). An increased RTD would lead to increased force-production in the part of the ROM where most of the muscle and work production occurs. It may also increase elastic energy storage and power amplification in the last part of the contraction when force production decreases (Azizi et al., 2008).

The results from the isokinetic knee extension test show that torque and work production did not increase for neither of the training modalities at slower velocities, whereas both training modalities increased leg press 1RM and power production at

higher loads. Thus, the high-load improvement was specific to the training movement and/or the involved muscles. At high-load, the primary determinant for power production is the muscle maximal strength (Duchateau & Hainaut, 1984). However, no hypertrophy of vastus lateralis was observed. Thus, the high-load improvement may be likely due to neural adaptations specific to the training movement, or improvement in the execution of the leg press. It is important to note that isokinetic leg extensions are much less complex than the leg press which requires coordination of several joints and muscle groups. Thus, it is possible that the improvement at high-load in the leg press was due to hypertrophy of other muscles than vastus lateralis. The lack of hypertrophy in vastus lateralis was surprising. It has previously been reported that high-load resistance training typically leads to hypertrophy (Folland & Williams, 2007; Narici et al., 1996b). A review article from Wernbom, Augustsson, and Thomee (2007) reported that resistance training in average results in a 0.2% increase in muscle CSA every day. Based on these results, we should have expected ~14% increase in muscle CSA. However, a possible explanation for the results in the present study may be due to the location where muscle thickness was measured (60% of the distance from the greater trochanter to the lateral epicondyle on the femur). There are some studies that have shown that the hypertrophy of the quadriceps is maximized at 40% of the femur length, and decreases distally towards to knee (Narici, Roi, Landoni, Minetti, & Cerretelli, 1989). Based on this study it cannot be excluded that hypertrophy may have occurred more proximally at vastus lateralis.

The present study demonstrated that very short and full ROM resistance training led to similar adaptations regarding the torque angle relationship and nearly similar work production measured in isokinetic knee extensions. Resistance training has previously shown to lead to an angle-specific increase in torque (Graves et al., 1989; Weir et al., 1995). Thus, the results in the present study are surprising since full ROM training is requiring muscle work over a larger angular range than very short ROM training, which was expected to be reflected in changes in optimal angle for torque production and a greater work production at more extended knee position. Interestingly, both training modalities resulted in similar improvement in work production at more extended knee position. This means that additional work the full ROM leg did in the last part of the

movement, did not benefit these parameters. Interestingly, we found that full ROM led to a significant greater work production in the first part of the ROM at an angular velocity of 300°s^{-1} . These results were surprising, and the possible mechanisms are unknown.

5.2. Change in contractile RTD

The changes in the rate of torque development after training were partly consistent with our hypothesis. We expected that both training modalities would lead to a similar improvement in RTD. The results show that there was an equal improvement in knee extension torque at 50 ms and 100 ms after torque onset. However, the very short ROM group had a significantly greater improvement in torque at 150 ms after torque onset. It is well documented that resistance training leads to neural and muscular adaptations which increases RFD (Duchateau & Hainaut, 1984; Vila-Cha, Falla, & Farina, 2010; Aagaard, 2003; Aagaard et al., 2002). Studies have shown that the early phase RFD is mostly influenced by neural factors such as muscle activation, while muscular factors such as muscle strength become more important when time from onset of force-production increases (de Ruyter et al., 2004; Folland et al., 2014; Aagaard et al., 2002).

The similar improvement in torque production at 50 ms and 100 ms after torque onset may indicate that both training modalities led to similar neural adaptations. These results show that explosive high-load resistance training can increase the early phase RFD. It has been suggested that high-velocity resistance training is superior to slow-velocity resistance training for improving early phase RFD (Maffiuletti et al., 2016). This idea is based among other things on the findings by Desmedt and Godaux (1977) showing that high-velocity resistance training produced 2-3 times higher discharge rate than slow contractions, and by Van Cutsem, Duchateau, and Hainaut (1998) whose study of ballistic dorsiflexion for 12 weeks resulted in a change towards ultra-high discharge rate behavior at the onset of muscle contraction. An increased discharge rate at the onset of muscle contraction will increase muscle activation and RFD in the early phase (Binder-Macleod & Kesar, 2005). There are some studies supporting the findings in the present study. For instance, Tillin and Folland (2014) investigated if explosive or

non-explosive isometric resistance training resulted in different adaptations. They reported that only explosive resistance training led to an increased early phase RFD. The increase in early phase RFD was ascribed to different neuromuscular adaptations, since explosive resistance training led to a significant greater EMG activity in the initial part of the contraction (Tillin & Folland, 2014). Additionally, Behm and Sale (1993a) reported that explosive isometric and dynamic contractions led to a similar increase in RFD, despite that the actual movement velocity differed between the groups. They suggested that the similar increase in RTD was mainly due to neural adaptations. Thus, it seems likely that the explosive execution of the contractions is more important than the actual movement velocity for increasing muscle activation and the early phase RFD. This could partially explain why explosive high load resistance training performed with very short and full ROM, led to a similar improvement in early phase RTD in this study.

The present study demonstrated that very short ROM resistance training led to a greater improvement in isometric knee extensions torque at 150 ms after torque onset. We can only speculate about the possible mechanism since there was no significant difference between the groups in any of the other tests. A possible explanation could be that very short ROM resistance training led to a greater increase in maximal isometric knee extension torque since the later phase of RFD is more related to the maximal strength (Andersen & Aagaard, 2006; Folland et al., 2014). However, we did not test maximal isometric knee extension torque, but the results from the isokinetic knee extension test show that there was a tendency for a greater improvement in torque at the slower velocities. An alternatively explanation could be that very short ROM had a slightly better improvement of early RFD (not detected statistically) that enable a faster force production when summed up at 150 ms. In other words, they became detectable statistically only after a longer time interval.

The results from the electrically induced contractions show that peak torque and torque at 50 ms after torque onset increased for both training modalities. Electrically evoked contractions are thought to represent the muscle capacity to produce contractile force since the nervous system would in theory not influence force production (Jenkins et al.,

2014). Thus, the increase in voluntary isometric knee extension RTD found in both training groups is not only due to neural but also muscular adaptations.

It is well documented that resistance training leads to muscular adaptations such as changes in muscle architecture, which is thought to influence the contractile properties of the muscle (Lieber & Fridén, 2000; Timmins et al., 2016). The present results show that there was no change in muscle thickness and a significant decrease in pennation angle and increased fascicle length in both training modalities. These results were surprising, because high load resistance training typical leads to hypertrophy and an increased pennation angle (Folland & Williams, 2007; Kawakami, Abe, Kuno, & Fukunaga, 1995; Aagaard et al., 2001). Interestingly, the adaptations found in this study is similar to as what Blazevich et al. (2003) reported after high-velocity resistance training. It has been suggested that the force and velocity characteristics of the exercise is influencing the adaptations in muscle architecture (Blazevich et al., 2003). Thus, the similar explosive execution of the contractions in the present study and the study by Blazevich et al. (2003), may explain the similar adaptations in muscle architecture.

The understanding of how muscle architecture influence RFD is currently incomplete. It is thought that muscle with less pennation angle is able to transmit the force more directedly to the tendon which is thought to be favorable for RFD (Maffiuletti et al., 2016). This idea has been supported by Spector, Gardiner, Zernicke, Roy, and Edgerton (1980) who reported that the impulse was greater in muscle with less pennation angle. Additionally, Erskine et al. (2014) reported that the percentage of change in pennation angle was inversely correlated with the percentage of change in normalized force at 150 ms after force onset. Thus, the decreased pennation angle found in the present study could explain the improvement in electrical evoked RTD.

The increased fascicle length found in the present study is thought to be beneficial for RTD. For instance, Earp et al. (2011) reported a positive correlation between an increase in gastrocnemius fascicle length and RFD. The possible mechanism for why an increased fascicle length is beneficial for RFD is due to the greater number of sarcomeres in series in longer fascicles, which will increase the maximal shortening

velocity of the fascicle (Lieber & Fridén, 2000). This will allow for a more rapid stretch of the passive series elastic structures of the muscle-tendon unit which will potentially increase the RFD (Wilkie, 1949). Additionally, the force produced from each sarcomere at a given shortening velocity will be greater in longer fascicles since each sarcomere will contract at a slower velocity (Lieber & Friden, 2000).

There is also some evidence that an increased fascicle length leads to decreased RFD (Blazevich, Cannavan, Horne, Coleman, & Aagaard, 2009). These results may challenge the theory that longer fascicles are beneficial for RFD. A downside with longer fascicle is that they possess higher compliance due to a greater extent of series elastic material (Maffiuletti et al., 2016). According to Edman and Josephson (2007) is the early rise in force production highly influenced by the ability to take up the series elastic slack in the muscle fibers. Thus, longer fascicles could also be linked to a slower RFD. However, it could be speculated that the benefit of longer fascicle exceeds the negative adaptations since fascicle length is strongly correlated to sprint performance which is highly influenced by RFD (Abe et al., 2001; Kumagai et al., 2000). Additionally, it is important to recognize that there are some methodological challenges when investigating how changes in muscle architecture influence RFD. It is very likely that changes in parameters such as muscle activation and tendon stiffness occur simultaneously, which is shown to also affect RFD (Maffiuletti et al., 2016). Thus, it is difficult to ascertain that the changes found in muscle architecture in the present study are responsible for the improved RTD.

Both training modalities led to a shortening of the delay between stimulation artifacts and onset torque. The delay between stimulation artifacts and onset torque is influenced by the time it takes to stretch the series elastic elements which are influenced by tendon stiffness and the excitation-coupling process (Nordez et al., 2009; Norman & Komi, 1979). The present study did not measure tendon stiffness directly. However, it is likely that both training modalities led to a stiffer tendon since increased tendon stiffness is typically reported after resistance training (Arampatzis, Karamanidis, & Albracht, 2007; Maffiuletti et al., 2016; Seynnes et al., 2009). The possible increased stiffness in the present study could explain the improvement in electrically evoked RTD since an

increased tendon stiffness is thought to improve RFD by a more efficient force transmission. This idea is supported by the study by Bojsen-Moller et al. (2005) who reported that there was a positive correlation between tendon stiffness and RTD.

The E-C involves several processes, but there is abundant evidence that the E-C is mainly governed by the entry of calcium through the sarcoplasmic reticulum (Melzer, Herrmann-Frank, & Luttgau, 1995). It is shown that resistance training can lead to an increase in the total amount of sarcoplasmic reticulum, and upregulation of dihydropyridine gene expression are observed in animals (Manttiri, Anttila, Kaakinen, & Jarvilehto, 2006; Ortenblad, Lunde, Levin, Andersen, & Pedersen, 2000). These adaptations are thought to be associated with an increase in calcium release rate (Ortenblad et al., 2000), which could explain the shortening of the delay between stimulation artifacts and onset torque found in the present study.

5.3. *Limitation of the study*

The most obvious limitation of this study is the use of intra-individual comparisons. The use of intra-individual comparisons, where the opposite limbs are trained with different methods can be criticized to lead to crossover-education-effect. It is well established that an increase in strength in the contralateral untrained limb occurs after resistance training. For instance, Adamson, MacQuaide, Helgerud, Hoff, and Kemi (2008) reported that the contralateral untrained limb experienced a small increase in peak force and RFD. The crossover effect is thought to be mediated by neural adaptation (Adamson et al., 2008). Thus, it is a possibility that the crossover-education-effect can explain the similar neural adaptations between the training modalities.

The electrically evoked contractions conducted in the present study was performed with single square wave pulses with 0.2 ms duration. It has been shown that higher stimulation such as octet (8 pulses at 300Hz) is necessary to achieve maximal RFD (Buckthorpe, Hannah, Pain, & Folland, 2012). The use of single-square pulses is not optimal for measuring the maximal intrinsic capacity of the MTU. This is, therefore, a limitation for our data.

5.4. *Practical applications*

The current findings have practical implications for not only athletes but also other individuals who want to enhance force production at high-velocities. Based on the results, it appears that performing explosive high-load resistance training with limited or full ROM would lead to similar improvements in force production at higher-velocities. These results may have particular implications for athletes with injuries that restrict the joint ROM. Furthermore, the use of high-load when performing explosive resistance training can have interesting implications for athletes wishing to maintain maximal strength. Additionally, the results from the present study strengthen the theory that the explosive execution of the contractions seems to be a vital stimulus regardless of the ROM or velocity for improving force-production at higher-velocities.

6. Conclusion

The results extend previous findings on the dorsiflexor muscles by showing that explosive resistance training of the knee-extensors leads to similar adaptations, irrespective of the ROM. The functional improvement in power production and isokinetic knee-extension torque at higher-velocities is associated with the increased RTD. The greater RTD is ascribed to neural and muscular adaptations improving rapid force production in the first part of the ROM, when most of the muscle force and work can be produced. Hence, owing to the greater work produced by the muscle fibers in the first part of the joint excursion, explosive training with very short ROM contractions may be just as effective as dynamic contractions to improve functional performance over full ROM.

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Abbreviations

Cm	Centimeter
CSA	Cross section area
CV	Coefficient of variance
E-C	Excitation-contraction coupling process
EMG	Electromyography
Hz	Hertz
ICC	Intraclass correlation
Kg	Kilogram
Min	Minutes
ms	Milliseconds
MTU	Muscle-tendon unit
MVC	Maximal voluntary contraction
Nm	Newton meters
Post-test	Test done after completing the intervention
Pre-test	Test done before the start of the intervention
RFD	Rate of force development
RM	Repetition maximum
ROM	Range of motion
RTD	Rate of torque development

Appendix

- I. Information to the participants (Norwegian)**
- II. Training program**

I Information to participants (Norwegian)

” Effekten av styrketrening på muskelens evne til å utvikle kraft hurtig: Isometriske vs. dynamiske kontraksjoner”

Bakgrunn og formål

Muskelens evne til å utvikle stor kraft hurtig er viktig i både daglige gjøremål og spesielt for prestasjonen i mange idretter. I idretter stiller krav til hurtighet (sprint), spenst, kast og slag/spark (kampsport) vil tiden for å utvikle kraft begrenset til under 250 ms, mens tiden muskelen behøver for å utvikle maksimal kraft er >300 ms. I denne studien ønsker vi å undersøke hva som er mest effektivt for å forbedre hurtig kraftutvikling, eksplosiv isometrisk eller dynamisk styrketrening. I tillegg ønsker vi å undersøke om de to treningsmetodene medfører fysiologiske tilpasninger som kan forklare endringer i hurtig kraftutvikling.

Dette prosjektet er et masterprosjekt ved Norges idrettshøgskole ved Seksjonen fysisk prestasjonsevne.

Vi søker etter forsøkspersoner i alderen 18-40 år som driver regelmessig styrketrening av underkroppen, dvs. >1 gang per uke de siste 12 mnd. Hvis du tilfredsstill disse kravene ønsker vi at du deltar som forsøksperson.

Hva innebærer deltakelse i studien?

Deltakere i denne studie skal gjennomføre en treningsperiode som varer i 10 uker med 3 økter i uken. Treningen vil bli gjennomført i Norges idrettshøgskole sitt treningssenter, og det vil være ukentlig oppfølging under treningene. Deltakerne vil trene den ene foten isometrisk og den andre dynamisk i et tradisjonelt beinpressapparat. Før treningsperioden vil det være nødvendig med en tilvenningsperiode der forsøkspersonene blir kjent med de ulike testene og treningsmetoden de skal gjennomføre. Før og etter treningsperiode vil det bli gjennomført flere tester: *Måling av*

muskelens kraftutvikling i dynamometer, muskelarkitektur ved hjelp av ultralyd, og muskelens effektproduksjon i beinpress. Testingen i dynamometeret vil isolere knestrekkerene og inkludere elektrisk stimulering av muskulaturen.

Deltagelse i denne studien vil kunne medføre noen ulemper. Det vil først og fremst krev tid til oppmøte for testing og trening. Når man gjennomfører styrketrening og fysiske tester er det alltid en risiko for at skader, men det er ingen grunn til å anta at skaderisikoen er høyere ved deltakelse i denne studien enn når man trener selv. Du må regne med å oppleve muskelstølheth etter både tester og trening. Elektrisk muskelstimulering (testing) kan oppleves ubehagelige/smertefullt, men er ikke skadelig.

Mulig fordeler med å være med i studien er økning i muskelstørrelse og muskelstyrke. I tillegg får man et innblikk i hvordan forskning foregår på NIH.

Hva skjer med informasjonen om deg?

Alle personopplysninger vil bli behandlet konfidensielt og aidentifisert. Det vil si at du får et forsøkspersonnummer som resultatene dine lagres under. Det vil finnes en kodeliste som kobler navnet ditt til dette forsøksnummeret, og denne listen vil oppbevares i en safe som kun prosjektmedarbeiderne og ledelsen ved Seksjon for fysisk prestasjonsevne ved NIH har tilgang til. Prosjektet skal etter planen avsluttes 1.juni 2019. Informasjonen om deg vil kunne bli lagret i 5 år for de blir anonymisert. Dine personopplysninger vil ikke kunne identifiseres i publikasjoner.

Deltakerne i denne studien vil ikke bli gjenkjent i publikasjoner.

Frivillig deltakelse

Det er frivillig å delta i studien, og du kan når som helst trekke deg fra studien uten å oppgi noen grunn. Dersom du trekker deg, vil alle opplysninger om deg bli slettet.

Dersom du ønsker å delta eller har spørsmål til studien, ta kontakt med Christian Solberg (Christiansolberg@icloud.com / 46744277), Olivier Seynnes

(Olivier.seynnes@nih.no), Gøran Paulsen, (Goran.Paulsen@olympiatoppen.no) eller Jens Bojsen-Møller (Jens.bojsen-moller@nih.no)

Studien er meldt til Personvernombudet for forskning, NSD - Norsk senter for forskningsdata AS.

Samtykke til deltakelse i studien

Jeg har mottatt informasjon om studien, og er villig til å delta

(Signert av prosjektdeltaker, dato)

II Training program

Week	Session	Rep	Sets	intensity	Total repetition
1	1	4	4	RM	64
	2	8	3	RM	
	3	6	4	RM	
2	1	4	5	RM	82
	2	8	4	RM	
	3	6	5	RM	
3	1	4	5	RM	82
	2	8	4	RM	
	3	6	5	RM	
4	1	4	4	RM	64
	2	8	3	RM	
	3	6	4	RM	
5	1	4	6	RM	86
	2	8	4	RM	
	3	6	5	RM	
6	1	4	6	RM	100
	2	8	5	RM	
	3	6	6	RM	
7	1	4	5	RM	76
	2	8	4	RM	
	3	6	4	RM	
8	1	4	6	RM	108
	2	8	6	RM	
	3	6	6	RM	
9	1	4	6	RM	108
	2	8	6	RM	
	3	6	6	RM	
10	1	4	4	RM	72
	2	8	4	RM	
	3	6	4	RM	