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264

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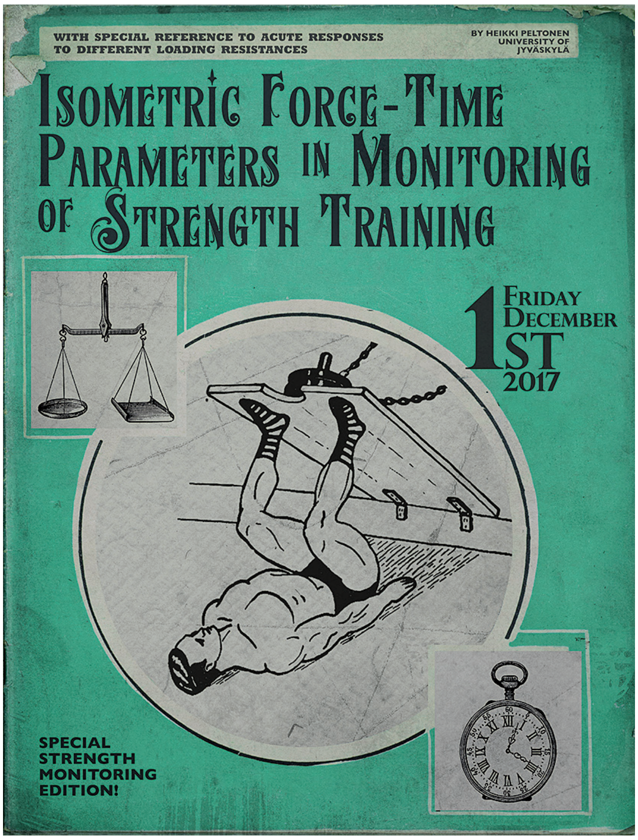
Isometric Force-Time Parameters in Monitoring of Strength Training

With Special Reference to Acute Responses to Different Loading Resistances



JYVÄSKYLÄN YLIOPISTO

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… in the physiological adaptation due to strength training,
as everywhere in the Nature…

…"endless forms most beautiful and most wonderful have been, and are being, evolved."

Charles Darwin
The Origin of Species

ABSTRACT

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Isometric force-time parameters in monitoring of strength training: with special reference to acute responses to different loading resistances
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The aim of the present series of studies was to investigate acute neuromuscular responses to (1) different strength training loadings and using (2) different external resistances. In addition, chronic adaptations and dynamic performances were compared to (3) the changes in isometric force-time parameters at the group level, and to (4) the individual timing of the improvement in the rate of force development (RFD) due to hypertrophic or maximum strength followed by power strength training periods. The latter one was achieved by systematic, repeated monitoring. Sixty-nine physically active men (20-35 yrs), but not experienced in resistance training, took part in the present series of studies. Cross-sectional study designs included hypertrophic (5 sets of 10 repetition maximum), power (5 sets of 5 repetitions at 40% of one repetition maximum) and maximum strength (15 sets of one repetition maximum) loadings using pneumatic and weight-stack devices with and without additional elastic resistances for the knee extensor muscles. During single explosive contractions, pneumatic resistance allowed greater power production at lower resistance levels due to higher velocities compared to weight-stack resistance. Conversely, weight-stack with additional elastic resistance increased power production due to greater torque towards the end of the movement compared to “pure” weight-stack resistance. However, during power strength loadings with explosive contractions, weight-stack resistance targeted the initial force production and, consequently, induced greater neuromuscular fatigue indicated by changes in muscle activity (EMG) during the first 100ms compared to pneumatic and weight-stack with elastic resistances. Nevertheless, greater resistance during weight-stack with elastic resistance induced greater central fatigue compared to “pure” weight-stack. Weight-stack resistance followed more closely maximal force production of muscles inducing greater peripheral fatigue during hypertrophic and maximum strength loadings compared to pneumatic resistance. Repeated maximal repetitions during maximum strength loadings also led to central fatigue during weight-stack resistance.

During the longitudinal study, time to reach peak RFD was identified as a potential parameter to differentiate adaptation between “peripheral and central focused” strength training, while the steepest phase of RFD may identify adaptations particularly during maximal strength/power training. Monitored isometric RFD parameters seemed to more sensitively and systematically reflect short-term responses from different training stimuli compared to peak isometric MVC. Nevertheless, MVC correlated strongly with the long-term changes in 1RM due to strength training. From the individual trainee’s perspective, the timing of the improvement in monitored RFD was related to baseline CSA and training-induced changes in anabolic and catabolic hormonal regulation. Based on these individual differences, RFD improved in one-third of the trainees following the maximum strength training period, one-third following the power strength training period, and the remaining one-third did not respond to either of the aforementioned training periods. Regularly repeated isometric monitoring during strength training could assist in tailoring training programs and selecting durations of the periodization cycles for each athlete, individually.

Keywords: strength training, monitoring, fatigue, adaptation, force production, isometric, maximum strength, power strength, hypertrophy

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Jyväskylä, November 2017
Heikki Peltonen

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following original articles, which are referred to in the text by their Roman numerals.

I Peltonen H, Häkkinen K, Avela J. Neuromuscular responses to different resistance loading protocols using pneumatic and weight stack devices. *Journal of Electromyography and Kinesiology*. 23:118-124, 2013.

II Peltonen H, Walker S, Häkkinen K, Avela J. Neuromuscular fatigue to power loading using a weight-stack device fitted with or without additional rubber band resistance. *Journal of Strength and Conditioning Research*. 28(7):1802-1811, 2014.

III Peltonen H, Walker S, Lähitie A, Häkkinen K, Avela J. Isometric parameters in the monitoring of maximal strength, power and hypertrophic resistance-training. *Applied Physiology, Nutrition, and Metabolism* (DOI:10.1139/apnm-2017-0310).

IV Peltonen H, Walker S, Hackney AC, Avela J, Häkkinen K. Increased rate of force development during periodized maximum strength and power training is highly individual. (Submitted for publication).

ABBREVIATIONS AND DEFINITIONS

½RT	half relaxation time
1RM	one repetition maximum
AL	activation level
ATP	adenosine triphosphate
C	cortisol
CK	creatine kinase
CSA	cross-sectional area
CV%	coefficient of variation %
DXA	dual-energy x-ray absorptiometry
ER	elastic resistance
EMG	electromyography
F100	force production between 0 to100ms.
FAI	free androgen index
FFT	fast fourier transformation
FT	free testosterone
HYP	hypertrophic
IEMG	integrated electromyogram
MF	median frequency
mmol	millimole
MS	maximum strength
MSP	maximum strength and followed power strength training
MU	motor unit
mV	millivolt
MVC	maximal voluntary contraction
M-wave	muscle compound action potential
N	newton
Nm	newton metre
P	power strength
PCr	phosphocreatine
PN	pneumatic
Rep	repetition
RF	rectus femoris
RFD	rate of force development
RM	repetition maximum
rmsEMG	root mean square electromyogram
RTD	rate of torque development
SHBG	sex hormone-binding globulin
T	testosterone
TT	total testosterone
VL	vastus lateralis
VM	vastus medialis
W	watt
WS	weight-stack

CONTENTS

1 INTRODUCTION

Training monitoring has been a common trend in endurance sports and activities over the past several years through the use of heart rate monitors, pedometers, cycling monitors etc. Nevertheless, athletes and enthusiasts, even the same ones as in endurance sport, train in the gym without any accurate training monitors- most trainees still keep a training diary by pen and paper. New miniature technologies and their lowered prices enable the development of new innovative monitoring solutions, however these solutions need valid parameters to follow adaptations in strength training as well. One possibility is to utilize isometric strength testing through in-built devices or retrofit sensors. Isometric measurements are easily standardized, require minimal familiarization for performance technique and are safe to perform maximally also during a fatigued condition compared to dynamic measurements (Blazevich & Cannavan 2007, pp. 130).

The physiology of the human body reacts to strength training in several ways, and thus neuromuscular adaptation via stress and fatigue is a multifaceted phenomenon from the aspects of time and complex causal dependencies. Therefore, one justifiable theoretical framework is that the performance outcome is the sum of all these physiological changes with performance technique, both in terms of improvement and impairment, due to a single-session of gym exercise and regularly repeated gym sessions (i.e. strength training). However, monitoring via only one training-specific parameter may overestimate the effect of this specific training and overlook or hide other aspects of changes in physiology of the trainee. Training specificity is a well-known and longstanding principle in the field of sport and exercise science (Baker et al. 1994). One potential benefit of using isometric strength tests to monitor improvements in the present study is that we may be able to identify more general adaptations, which are apparent regardless of contraction-mode, during dynamic strength loading and training.

The present literature review of this thesis focuses on the use of monitoring tests with strength training devices, which follow the development of the trainee during goal-oriented strength training and physiological qualities underpinning performance. The individual research articles of this thesis focused on examination of the acute responses and recovery after different strength training goal-oriented loadings, as well as the differences between these acute response when using the most widely available resistance modes; pneumatic and weight-stack with and without elastic resistance – and how monitoring parameters indicate their differences in producing acute fatigue. Finally, monitoring should identify individual changes and separate responses from different stimuli during periodized strength training, which was the focus in the last part of this thesis.

The studies introduced in this thesis were designed to increase the reader's scientific knowledge on the application of different resistance modes to support efficacious goal-oriented training. Additionally, the reader will benefit from the presented methods for monitoring training effects and utilize this information to tailor strength training progress for individual athletes and enthusiasts. Optimal strength training requires individual capabilities to respond and adapt to specific training stimuli, which should be taken into account when designing optimal strength training programs.

2 REVIEW OF LITERATURE

2.1 Background of strength training monitoring

Parameters, which describe actions during strength training, training-induced acute fatigue and possible development due to training are essential elements of training monitoring. Monitoring is a tool in itself and systematically collected data should be the base for individual prediction of the development of the athlete towards a specific training goal. Nowadays, this prediction is still subjective and strongly associated with knowledge and personal experience of an athlete's strength coach (Borresen & Lambert 2009), but the increased amount of monitoring devices with expanded collected individual data and databases make it possible to utilize different models to optimize strength training in practice during the near future.

Theories of the adaptation process of the human body for stress developed by Hans Selye since 1936 (General Adaptation Syndrome) and Nikolai Yakovlev discovered and defined the phenomenon of "super-compensation" during recovery after training stimulus-induced fatigue (Viru 2002). Along with these studies and the early work of Bannister et al. (1975), several researchers have modelled development and adaptation due to physical loading-induced fatigue via mathematical system theories. In these studies, the mathematical function of the modelled performance follows the form, where the constant adjusts the magnitude of the fatigue (detriment) effect relative to the fitness effect (Fig. 1) (Jobson et al. 2009). These are called "impulse-response" concepts, which are based on linear mathematical models and include dynamic and temporal characteristics of training. However, the actual strength gain and neuromuscular adaptation is a complex non-linear phenomenon and, therefore, alternative mathematical approaches may offer more accurate models (e.g. multi-layer neural network (Edelmann-Nusser et al. 2002), dynamic meta-model (Perl 2004), regression analysis models (Mujika et al. 1996), mixed linear model and cluster analysis (Avalos et al. 2003)) to predict performance.

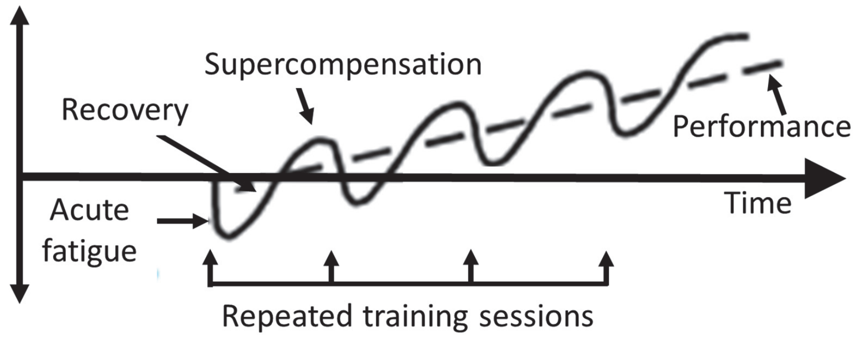

FIGURE 1. Fitness-fatigue model for the super-compensation process (Modified from Häkkinen 1990, pp. 55).

Training optimization via these prediction models requires the quantification of intensity and volume during a training session, and this is called the training "dose" (Jobson et al. 2009). Several studies have quantified a wide range of physiological parameters (e.g. heart rate, oxygen consumption, cycling power, lactate) related to aerobic capacity during endurance training. Unfortunately, strength training includes numerous independent variables that elicit training adaptations (Scott et al. 2016) and no universal method to quantify a training dose for optimization of strength training was found. Busso et al. (1990) and Desgorces et al. (2007) calculated training dose (or impulse) based on lifted repetitions with %1RM and, further, Busso et al. (1990, 1992) compared this data to endocrinal responses. However, these load-volume related fatigue parameters were valid only for one aspect of strength training. The individual's performance capacity depends on training background and it includes daily variation, thus, quantification of training dose could be more reliable when related to specific parameters, which reflect multifaceted training session-induced fatigue.

2.2 Acute responses and long-term adaptations in strength training

The origin of neuromuscular fatigue has been classified as either central or peripheral fatigue (Bigland-Ritchie et al. 1978). Peripheral fatigue due to strength loading can further be sub-classified into metabolic and mechanical fatigue. Moreover, strength training leads to several other changes in the body e.g. endocrinal changes, if exercise has been sufficient in intensity and duration. Recovery of each aspect begins immediately after loading, however different processes take a specific time to return to their initial level or upgrade their capacity before the start of the next loading. Fatigue is a complex phenomenon due to multifaceted neural fatigue from the upper brain center to peripheral excitation of the muscle. During the action, probably certain mechanisms might already be fatigued in the body, when disparate mechanisms just begin to '*warm-*

up'. However, this could also be a safety or compensation mechanism in order to maintain the desired function. In general, fatigue in the neuromuscular system is characterized by its inability to produce or sustain a maximal force level voluntarily. Therefore, training monitoring parameters of fatigue should primarily reflect the reduction of performance, and secondarily the reasons behind the decreased performance capacity (Fig. 2).

a) b)

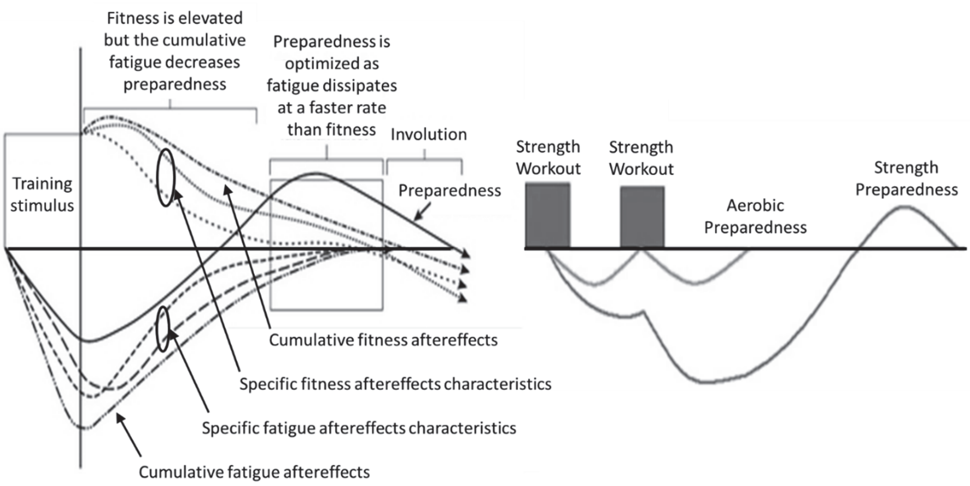

FIGURE 2. a) Schematic graph of the specific fitness and fatigue characteristics for super-compensation (Adapted from Haff & Haff 2012, pp. 215 with Hoffman 2012; Stone et al. 2007; Chiu & Barnes 2003); b) preparedness to different stimuli e.g. strength workout (Turner 2011 with Zatsiorsky & Kraemer 2006).

Biological limits adjust the body's capacity to adapt to training and, therefore, define how different strength properties can improve. Individuals with no resistance training background possess a large window of adaptation and, usually, in the beginning of strength training they will elicit large and rapid improvements. Otherwise, high-level athletes are closer to their own full physiological potential and thus, their training requires systematic and sophisticated programs to maintain or improve their capacity even further (Fleck & Kraemer 2004, pp. 64).

Systematic training programs with varied loadings should cause specific and desirable responses. An individual's training background, genetics and life outside the gym environment bring inter-individual variations to these strength training responses; however, training monitoring could give tools for the modification of a training program and even daily variation in performance. Strength training might include several goals, but simply the targets could be categorized as to increase the maximum weight to lift in maximum strength training or lift the allocated weight as fast as possible in power training. In addition, strength training might also include non-performance related goals, as for example, muscle hypertrophy, which could be related at least partly to enhanced maximum strength and muscle endurance properties. Generally, the goal of strength training should be the long-term adaptation of the cumulative training effect for specific aspects of strength or the improvement of other sport performance (Gambetta 2007).

2.2.1 Maximum strength training

Maximum strength includes both neural and muscular components. Typically, "pure" maximal strength exercise consists 1 to 5 sets with 1 to 6 repetitions using high loads (from 85–100% of 1RM loads). Every set should be performed after a relatively long recovery period (3 to 5 min or even up to 7 min) and, thus with (near) maximally refilled phosphate storages in the muscle (Fig. 3).

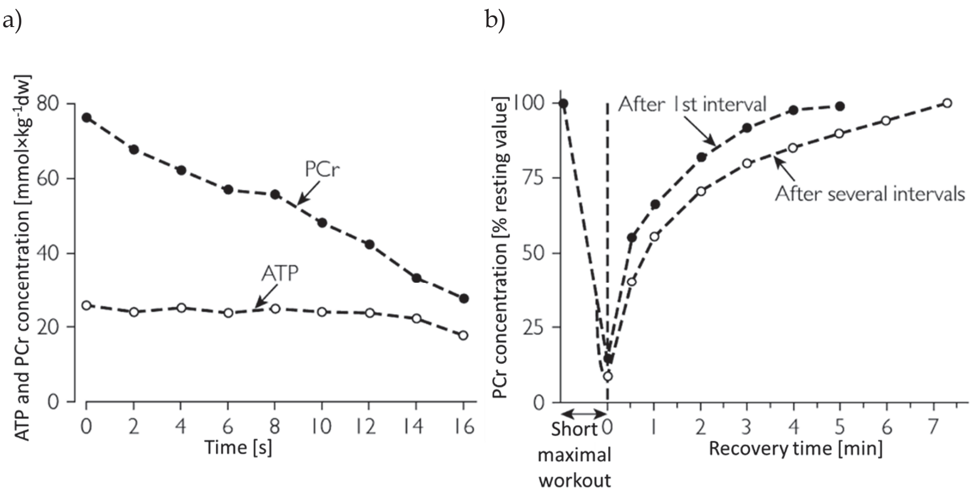

FIGURE 3 The time courses for a) the utilization and b) the re-synthesis of phosphate storages during and after short maximal workout (Modified from MacDougall & Sale 2014, pp. 19).

In addition, three minutes of recovery is usually enough to return the release of chemical transmitters to normal levels in the neuromuscular junction. However, an even longer recovery between sets is necessary for transmission of nerve impulses in the central nervous system in order to allow fast twitch fibers to act and generate high force levels during maximum strength training (Bompa et al. 2013, pp. 51).

Isometric maximal force may decrease ~15% and the rate of force production ~25% during maximum strength exercise (McCaulley et al. 2009). McCaulley et al. (2009) observed that neural fatigue may be greater after higher intensity maximum strength exercise compared to hypertrophic exercise with equal total work, which could cause the delay of the recovery of force production after maximum strength exercise (~1/3 during 60 minutes). On the other hand, hormonal responses due to maximum strength exercise are lower compared to exercises with greater total work (Smilios et al. 2003). From a metabolic aspect, the time needed for supercompensation is 24 hours or more, but mechanical and neural stress due to near maximal force levels might require even more time (72 hours) to recover completely (Bompa et al. 2013, pp. 56).

Neural adaptations to maximum strength training consist primarily of enhanced maximal motor unit recruitment and firing rate (Moritani & DeVries 1979; Häkkinen & Komi 1983; Knight & Kamen 2001; Kamen & Knight 2004) increased spinal motoneuronal excitability and, thus enhanced efferent motor drive (Aagaard et al. 2002a; 2002b). Depending on the training goal, maximal strength could increase also via peripheral adaptations including the improvements in muscle contractile properties (Lattier et al. 2003, Paasuke et al. 1999), type II/I fiber area ratios (Sleivert et al. 1995), and muscle cross-sectional area (Häkkinen & Keskinen 1989; Sleivert et al. 1995) occurring in parallel with neural adaptations. These neural and muscular adaptations are linked together closely, because type II muscle fibers usually have larger CSA, faster conduction velocity and greater maximal firing rate compared to type I muscle fibers (Staron et al. 1994). The time-course for increases of t muscle strength due to neural factors could be theoretically the recovery time. However, the time needed to integrate and activate new myofibrillar proteins within the muscle fiber is not known, as well as when they contribute to enhanced force production (Phillips 2000). In addition, the complexity of the movement can affect the time to learn effective activation patterns between agonist, antagonist and synergist muscles for specified exercise (Fig. 4).

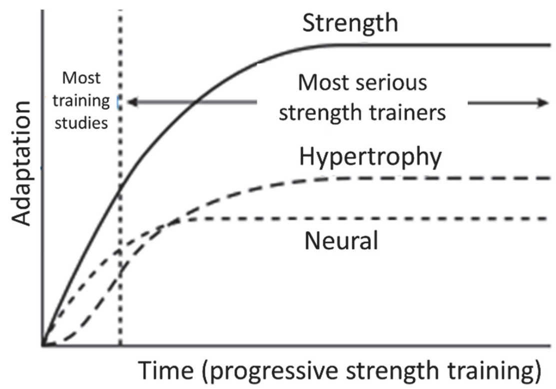

FIGURE 4. The relative roles of neural and muscular adaptations due to continuous and progressive maximum strength training (Modified from Sale 2003, pp. 305).

2.2.2 Power strength training

Typical power (explosive) strength training utilizes lower loads such as 30–60% of 1RM, but contraction velocities should be as high as possible in each repetition throughout the whole exercise (e.g. 5 × 5 reps). Maximum strength training requires also maximal contraction effort, however, lower loading volume in power training enables gains in explosive force production (Barry et al. 2004; Greertsen et al. 2008; Gruber et al. 2007). It has also been shown that acute effects of power resistance exercise primarily reduce rapid force production and muscle activity rather than maximal force output (Linnamo et al. 1998). On the other hand, higher accelerations and movement velocities are possible when there is a difference between the current resistance force and maximal force production capabilities of the muscles. Thus, this permits primarily high velocity improvements due to high velocity repetitions, for example, in ballistic or plyometric type power training (Komi & Tesch 1979; Häkkinen et al. 1985b; Sale 1988).

Maximum contraction effort has been observed to improve agonist and antagonist coactivation, agonist/antagonist activation patterns, motor unit rate gradation and synchronization, and the use of type II muscle fiber motor units (Sale 1988). In the beginning of maximal rapid muscle contraction, force production increases more than twofold during the first 10 to 50 twitches due to increased firing frequency before a plateau is reached. All possible factors of this staircase effect are not known, but the main reasons that have been suggested are increased calcium in the cytosol because of increasing release of calcium ions from the sarcoplasmic reticulum with every muscle action potential and also because of failure to recapture the calcium ions immediately after binding of cross bridges (Guyton & Hall, 1996, pp. 83).

Greenhaff & Timmons (1998) observed that the rate of ATP re-synthesis based on phosphocreatine increased to the highest possible rate of energy expenditure during the first 2 seconds from the beginning of the exercise. In addition, after the first repetition elastic structures assist power production via the stretch-shortening cycle. At the same time, post-activation potentiation increases e.g. sensitivity of calcium transfer and, thus, effectiveness of muscle contractions without the accumulation of fatigue (Tillin & Bishop 2009). If the set is longer and exercise continues over next seconds (from the 3rd to 5th second) the rate of the phosphocreatine breakdown decreases, but its rate still exceeds the rate of anaerobic glycolysis. Generally, the exercise duration from 5 to 15 seconds stresses the capacity of the phosphocreatine mechanism (Viru & Viru 2001, pp. 144).

Otherwise, in physics, power is the amount of energy consumed per time unit and it is the rate of doing mechanical work. In anaerobic performances, as is the case for short-term "power strength" exercise, the metabolic process that supplies energy is more complex than during endurance exercises with steady-state aerobic events, which are directly related to metabolic power (Garhammar 1993). This anaerobic working efficiency is around 25% related to energy expenditure (Åstrand & Rodahl 1977, pp. 99) (Fig. 5). It is well-documented that during rapid recruitment and high power generation phosphocreatine breakdown is the main energy source in the high intensity performance and at the onset of exercise.

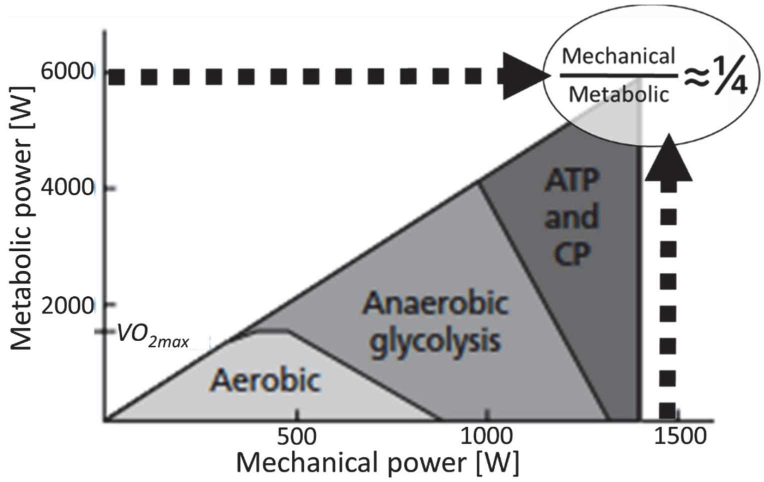

FIGURE 5. Working efficiency during short and maximal contraction (Modified from Knuttgen & Komi 2003, pp. 4).

From a metabolic point of view, the amount of energy that can be produced from phosphocreatine is restricted by the amount of phosphocreatine stored. The power generation during the first few seconds of performance is limited by the ability to utilize ATP rather than by the rate of ATP re-synthesis, because fast-twitch fibers include approximate 20% greater phosphocreatine concentrations compared to slow-twitch fibers (Hultman et al. 1983; Henriksson & Sahlin 2003). The study of He et al. (2000) observed that the contraction of fast-twitch fibers costs three- to four-times more energy compared to slow-twitch fibers. In practice, explosive contractions include greater increases in the rate of energy expenditure than slow contractions or contractions with heavier loads, when exercise work and total kilograms lifted were standardized (Mazzetti et al. 2007). Nevertheless, a typical power loading accompanied by minor blood lactate concentrations, is associated with acute central fatigue and/or impaired neuromuscular propagation without remarkable peripheral fatigue (Fleck & Kraemer 2004, pp. 99).

2.2.3 Hypertrophic strength training

The aim of hypertrophic type loading is to activate and cause acute stress in all motor units in the specific muscle. It is well-known, that the amount of work done plays an important role together with work intensity and the duration of the recovery phase in generating muscle growth (Patterson et al. 1985; Kraemer et al. 1990; Fitts & Widrick 1996; Wernbom et al. 2007), which is the goal of hypertrophic training. Typical hypertrophic exercise includes 70-85% of 1RM load and several sets with relatively short resting periods (from 30 to 120 s.) between moderate set lengths (from 8 to 12 repetitions). A relatively short resting period between sets is not enough for full recovery and fatigue cumulates set by set due to this exercise (Kraemer et al. 1990; Häkkinen et al. 1993; Walker et al. 2012; Ruotsalainen et al. 2014).

High training volume load (repetitions × resistance) consumes phosphate storages in the muscle during each set. Short resting periods between sets accumulates a phosphate deficit and creates the need for anaerobic glycolysis in ATP production, and thus induces an anabolic response through the stress of the metabolic system (Häkkinen & Pakarinen 1993; Kraemer et al. 1993). Therefore, the time needed for supercompensation is around 36 hours or more (Bompa et al. 2013, pp. 45). In addition to metabolic stress, a high number of repetitions and relatively high resistance induces strain and stretch to mechanical structures of the muscle tissue, which then causes damages in the weakest sarcomeres. These myotraumas have been associated to an acute inflammatory response and increased cytokine levels. All these peripheral changes disturb force production of the muscle and may lead to a decrease of 50% or more in maximal force levels (Häkkinen & Pakarinen 1995; Walker et al. 2013) with ~30% decrease in the rate of force production (McCaulley et al. 2009) immediately after hypertrophic loading. Both of these force production parameters recovered to half of the baseline values during 60 minutes after the cessation of the exercise. However, complete recovery after hypertrophic exercise based on isometric force production might take 48 hours (McCaulley et al. 2009).

These repetitions with moderate or relatively high resistance (at the end of the sets) stress the neural system and may, thus cause central fatigue. Several studies have shown enhanced neural activation of agonist muscles even though the force output remains constant during loading. This increased activation is due to increased recruitment of motor units and their firing frequencies, which is the first sign of fatigue in hypertrophic loading (Adam & DeLuca 2005). After that, if the duration of sustained near maximal or maximal contraction continues, the firing frequency of motor units' decreases (Nybo & Nielsen 2001). Relatively slow lifting tempo during concentric and eccentric phases of repeated repetitions causes a relatively long time-under-tension in all different motor units. Long contraction times at moderate or high resistance may require recruitment of higher threshold motor units to compensate for fatigue induced in previously recruited motor units. During the set, muscle activity, assessed by surface EMG, could increase repetition by repetition, despite a reduction in median frequency (Fig. 6) (Walker et al. 2012).

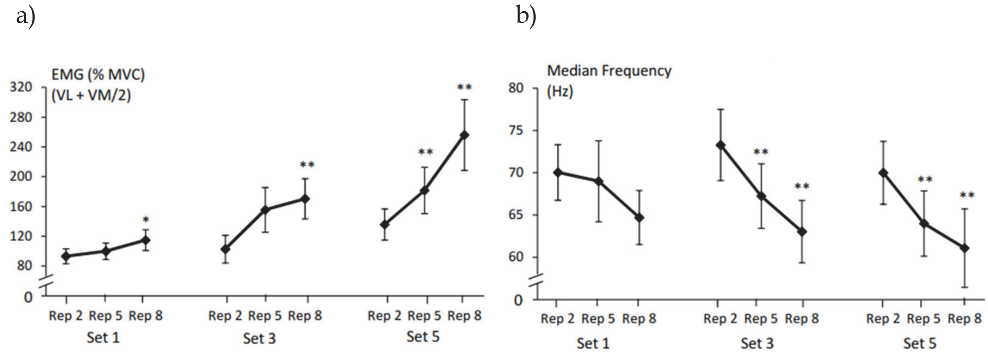

FIGURE 6 a) Muscle activity and b) median frequency from combined vastus lateralis and medialis muscles during sets of hypertrophic loading (Walker et al. 2012).

Increased EMG amplitude with concomitant reductions in median frequency could indicate increased motor unit synchronization (Weytjens & van Steenberghe 1984; Yao et al. 2000; Dartnell et al. 2008) and/or increased muscle temperature (Petrofsky & Lind 1980), which may improve transmission of collected signals. In addition, high number of repetitions and relatively high resistance induces strain and stretch in mechanical structures in the muscle tissue, which can cause beneficial responses in molecular and cellular level for muscle growth in both myofibers and satellite cells (Toigo 2006). These myotraumas have been associated with an acute inflammatory response, which is believed to release growth factors that adjust functioning of satellite cells (Toigo et al. 2006; Vierck et al. 2000). Concurrently, the changes in acidic environment may promote also muscle growth (Buresh et al. 2009). Sufficient volume load /time-under-tension increases circulating concentrations of testosterone (~20-30%), sex-hormone binding globulin (~30%), and cortisol (~10% or more) until the end of exercise, however serum hormone levels revert to baseline during 30 or 60 minutes after a training session (Ahtiainen et al. 2011; McCaulley et al. 2009). Training until failure with low (30% 1RM) or high (80% 1RM) load seems to cause similar increases in the molecular response, however, muscle strength increases more after high load training due to greater neural adaptations (Haun et al. 2017; Jenkins et al. 2017).

The increased muscle cross-sectional area due to training is based mainly on hypertrophy of fast twitch fibers with less hypertrophy of slow twitch fibers in the muscle. Along with this, mitochondrial density decreases, and thus, promotes anaerobic capacity with enhanced rate of muscle glycogen synthesis (Tesch 1988). The time course of muscle hypertrophy is dependent upon the type of training program (Conley et al. 1997; Akima et al. 1999), nutrition (Biolo et al. 1997), training background of the trainee (Alway et al. 1992) and genetic factors, which can affect hormonal regulation, local growth factor and membrane permeability of ions, selectively (Phillips 2000). Measurable increases in muscle hypertrophy could appear after 6-7 weeks of hypertrophic type training, but it is reasonable to speculate that the volume density of muscle fibers increases earlier e.g. in 3-4 weeks depending on the measuring method (Häkkinen et al. 1985; Kraemer et al. 1990; Phillips 2000).

2.3 Unique characteristics of resistances with and without mass

Two of the most widespread resistances in the training devices in commercial gyms are the weight-stack and pneumatic resistances. With lever arms and/or the cam of these in device structures, it is possible to customize the resistance and adjust it to follow the changes of human torque production at different joint angles. This is called variable resistance. Torque production capabilities are known to be partly related to joint angle (Singh & Karpovich 1966) and contraction velocity (Komi 1974). Therefore, optimal variable resistance could cause desired stress levels to the neuromuscular system over the entire range of movement (Graves et al. 1989). However, changes in contraction velocities and in the amount of momentum affect forces exerted by the neuromuscular system, and should be considered when evaluating the properties of different resistances. Häkkinen et al. (1987; 1988b) investigated weight-stack loading with variable resistance and Frost et al. (2008) have studied pneumatic resistance repetitions with different velocities and loads with muscular activities recorded during the trials. Nevertheless, the differences between various resistance modes has not been investigated comprehensively using different strength training loading schemes (e.g. maximal strength, muscle hypertrophy and power).

The exact responses of the neuromuscular system might be related to the specific type of loading (e.g. power loading). One possibility for the "targeted" effect of a weight-stack's mass and inertia compared to velocity-based pneumatic or additional elastic resistance is, for example, when performing explosive actions with weight-based resistance; the movement is performed for as little as 50% of the whole range of motion under a muscle activation strategy aiming to accelerate the action (Newton et al. 1997). However, if there are differences between resistance modes in terms of how the resistance is produced throughout the range of motion, there may also be differing amounts of work, muscle tension, and, therefore, muscle activity and rate of total work done between these modes. Frost et al. (2010) suggested this possibility but to our knowledge no studies have directly compared these main resistance modes.

2.3.1 Weight-stack –resistance

Categorization of the characteristic of the resistances are based typically on their different inertial properties. The acceleration of the weight-based resistance, body weight or only the weight of the limb is proportional to the force generated or inversely to its mass or inertia. This is based on the Newton's second law of motion:

$$F = m \times a,$$

where F is the sum of all external forces; m is the mass of an object and a is the acceleration of the object. The components, which were included in this equation are possible to separate. A further equation shows weight (W) and inertia (I) based force (F) components with gravity (g) (Djuric et al. 2016):

$$F = m \times g + m \times a = W + I.$$

The frame and rails of a weight-stack device simplify the movement of the weight in the vertical plane. The resistance provided by a weight-stack device is composed almost entirely of mass, and is thereby influenced by inertia and momentum. The weight of the stack represents a constant force, inertia changes over time depending upon the acceleration of the mass. Therefore, the actual load is not maintained throughout the range of motion, rather it is changed as a function of weight-stack acceleration.

2.3.2 Pneumatic –resistance

In strength training devices, pneumatic resistance is proportional to the air pressure in the cylinder and can be modified by lever arms of the structure, whereas the device's frame weight provides only a minor contribution to the total resistance and inertia is minimal (see Fig. 7). The pneumatic resistance in the cylinder is constant throughout the range of motion and is independent of contraction velocity or acceleration.

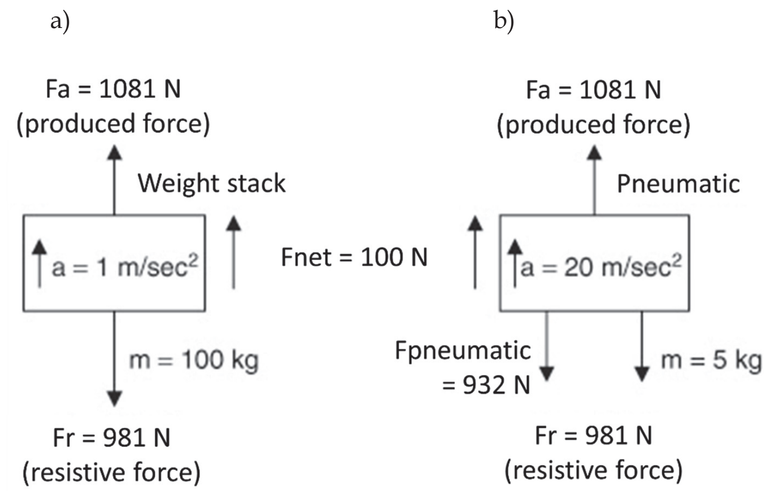

FIGURE 7A Theoretical comparison between a) weight-stack and b) pneumatic resistance (Frost et al. 2010).

Therefore, resistance in the beginning of the concentric movement is lower compared to e.g. weight-stack, when movement accelerates faster. Therefore, mean velocities and power output are higher as also peak values, if the shortening properties of the muscles were not limited during contraction.

$$P = \frac{Fpneumatic}{A},$$

where P is the air pressure; Fpneumatic is the sum of all external forces and A is the area of piston, which the air is compressed.

2.3.3 Combined elastic and weight-stack –resistance

Especially during explosive repetitions, the effects of elastic bands govern the inertial properties of a weight-stack (Frost et al. 2010) creating a steadier and greater total resistance throughout the concentric phase of the movement, but also adding workload during the eccentric phase (Cronin et al. 2003). Total resistance is based on the equation:

$$F_{total} = F_{weight} + F_{band},$$

where Fweight is gravitational force of the weight-stack and Fband is the additional elastic resistance; its effect is according to equation (Hooke's law):

$$F_{band} = -k \times l,$$

where k is the specific stretch coefficient of the elastic band and l is the distance that the elastic band is being extended.

According to these equations, the additional elastic band increases the load and may modify the fatigue distribution in the neuromuscular system and, therefore, maximum force production may also be affected by e.g. acute power loading. This change in resistance mechanics may eventually lead to training-induced improvements in both explosive and maximal force capabilities during power training. In addition, improved maximal strength is associated with enhanced rapid force production (Aagaard et al. 2002; Andersen et al. 2006; Anderssen et al. 2010), but explosive strength training leads to greater increases in RFD compared to high-load heavy resistance training (Häkkinen et al. 1995a; 1995b). However, explosive actions with combined weights and elastic bands may be advantageous in some situations compared to single resistance mode techniques.

2.4 Opportunities and challenges in monitoring of strength training

2.4.1 Aspects of monitoring in strength training

During the last decades, several studies have detected different parameters for monitoring strength training. Although these studies' prediction formulas may accurately estimate the average changes in parameters for a specific subject group as a reference, it may not necessarily reflect accurate estimations for all athletes (Heyward and Gibson 2014). In addition, the technical level and performance capacity of the testing devices have been low, and this might have complicated testing in several ways in the gym environment during the past years. In spite of that, the same methodological questions arose then as nowadays (Hettinger 1961).

In the beginning of the 1980s, the first computers were utilized to support strength training. These early solutions included manual data inputs, simple analysis and listform outputs (LeDuc & Meleski 1986) compared to the present or near future training monitors with filtered multichannel data from different sensors and visual feedback-based complex calculations. Multifaceted strength training aspects require specific indicators for different training targets (McGuigan & Foster, 2004), as the schematic presentation shows in Fig. 8a. Advanced and sophisticated sensors track performances and produce detailed data, thus, more accurate information are available for athletes and coaches. However, monitoring acute responses and short-term adaptations following strength training sessions is still problematic. One of the fundamental uses of trainee monitoring in strength training is to inform adjustments to training program prescription (Foster et al. 1998). There is a lack of standardized and universally accepted methods and parameters of monitoring strength training. Our knowledge is limited; what does this data really reflect, is there a need to modify a training program based on that data and how we should update it?

In the field of strength training (Fig. 8a), monitoring parameters are possible to be represented as a triangle shape between three main variables; force, time, and distance, with conducted variables; mechanical work, velocity, power, and force production with time function (Fig. 8b). Therefore, the one repetition maximum or the highest load lifted is only one aspect of strength properties. Some authors (Buckner et al. 2016) suggest that 1RM is (like) a specific skill, which will increase most due to training with near-maximal loads.

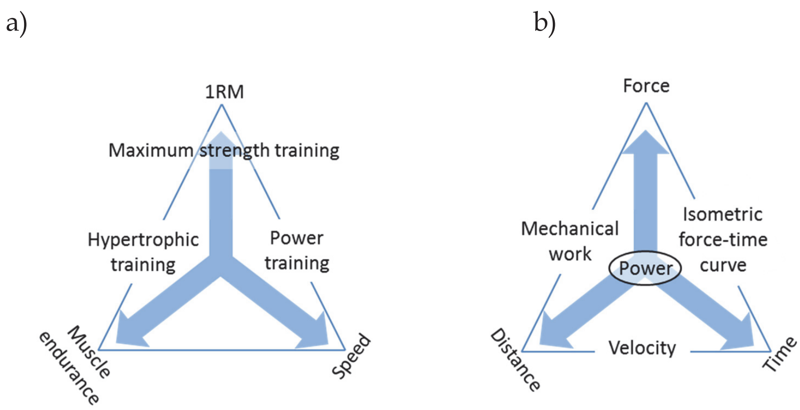

FIGURE 8. a) Relationships between strength training goals and types, b) Relationships between kinetic and kinematic variables in strength training monitoring.

Naturally, 1RM is the main variable for some trainees (e.g. weightlifters) and the improvement of 1RM is the final target for designing a strength training program in this population. However, it is well known that strength training could also increase muscle contraction speed and muscle endurance properties and, thus, when monitoring only one aspect others will be overlooked. Individual variation between strength training responders and non-responders is related to the measured variable, since all trainees can improve in one way or another if training volume and intensity are sufficient enough (Churchward-Venne et al. 2015).

The effective use of monitoring supports the coach-athlete co-operation in several ways. The monitoring should offer tools to evaluate an athlete's potential and current training status. In addition, the ideal monitoring should be able to identify how the athletes respond to the current training program and support the day-to-day decisions of the coach regarding modifying the training program. However, measuring training progress related to specific training goals and to link this information into (sport) performance are major challenges in the field of monitoring (Foster et al. 2017).

Strength training monitoring could be categorized as e.g. internal and external loads. The methods, such as RPE-queries and heart rate recorders, to monitor internal loads provide useful information on how the athlete or subject is feeling or adapting to training. Internal load includes both the psychological and physiological load imposed on the subject or athlete (McGuigan 2017). However, internal load is a secondary variable compared to external load, if collected information is contradictory. Specifically, Vasquez et al. (2013) report that the use of RPE-queries as a way to monitor training load and resistance training can be misleading when the strength training is being performed to muscular failure. Therefore, the primary focus of this thesis was monitoring external load via different outcomes of strength training related performances.

2.4.1.1 Maximal strength evaluation

1RM. A typical method to determine one aspect of maximal strength is performing dynamic 1RM with constant resistance (e.g. free weight or simple pulley device), which is movement and contraction mode specific. For example, the concentric contraction of the same muscle is greater when it immediately follows eccentric action (Komi & Bosco 1978). 1RM describes maximal force production over the sticking point during the whole range of movement, when produced momentum is enough to exceed this weak joint angle (Elliot et al. 1989). Variable resistance can increase resistance before and after this sticking point, and thus compromises velocities during maximum force production. Therefore, lifted mechanical workload is usually greater per each repetition by variable resistance compared to constant resistance.

A broader overview of an individual's maximal strength is possible to determine, when adding up the result of several exercises together e.g. bench press, squat and deadlift in powerlifting competitions or snatch and clean and jerk in Olympic weightlifting. However, maximal strength varies with lifter's body mass and in some situations, it is necessary to compare the lifted weights between different individuals. One option is simply to calculate a ratio score, where the lifted weight is divided by the lifter's body mass. Unfortunately, this method assumes the body mass exponent to be one, but based on the study of Croucher et al. (1984) with men's world-record Olympic-style lifters the body mass exponent should be 0.58. Batterham & George (1997) determined the range of body mass exponent to be from 0.45 to 0.48 for men and women World Weightlifting Championships competitors, respectively. In addition, Hui et al. (1995) found that the exponent range is between 0.73 and 0.87 in isometric condition. Another option is to use weight classes e.g. the lightest, the intermediate or the heaviest weight classes, which compromises the effect of body mass and helps the audience to follow the competition. In a tie situation, a lighter lifter is the winner. In some competitions, there is a need to coronate/choose the "Overall winner" or the "Champion of Champions" from the lifters in different weight classes or sexes. For example, the International Powerlifting Federation (IPF) uses the Wilks formula for this comparison. The total weight lifted is multiplied by the Wilks's coefficient, which is Wilks's score and, thus the final result:

$$Wilks's\ coefficient = \frac{500}{a+bx+cx^2+dx^3+ex^4+fx^5},$$

Constant	**for men:**	**for women:**
a	-216.0475144	594.31747775582
b	16.2606339	-27.23842536447
c	-0.002388645	0.82112226871
d	-0.00113732	-0.00930733913
e	7.01863E-06	0.00004731582
f	-1.291E-08	-0.00000009054

where x is the body weight of the lifter (kg).

The study of Vanderburgh & Batterham (1999) showed that the Wilks formula seems to be a valid method to adjust powerlifting results by body mass. However, Wilks coefficient emphasizes more absolute strength of the lifter than relative strength (normalized to lifter's mass). In Olympic weightlifting, the International Weightlifting Federation uses the Sinclair coefficients, which are related to a lifter's own body weight, the world record holder's body weight and the world record of the heaviest bodyweight category in the recent Olympic cycle:

$$Sinclair\ coefficient = 10^{A(log10\left(\frac{x}{b}\right))^2},$$

Constant	for men:	for women:
A	0.794358141	0.897260740
b	174.393	148.026

where x is body weight of the lifter (kg). If x < b, b is the recent world record lifter's body weight (kg) in the heaviest weight category and A is the calculated coefficient for this recent Olympiad, or 1 if x ≥ b. The recent Sinclair coefficient values are based on the results of Olympiad from 2013 to 2016.

Repetitions to failure. In some practical cases, exact knowledge about maximal strength is not necessary and it might be more important to avoid, for example, injury risk due to single repetition with high weights. For example, the 10RM load is useful in resistance training for clinical purposes (DeLorme & Watkins, 1948). In addition, the 1RM approximation can be made based on the amount of repetitions before failure with a correlation formula, which explains and adapts the relative load from 1RM based on reference data. The accuracy of these evaluations depends on this reference data; such as the type of the exercise and the device, population and their training background (Braith et al. 1993; Dohoney et al. 2002). As an example, the formula from the study of Brzycki (1993) can be seen below:

$$Predicted\ 1RM = \frac{Weight\ (kg)}{(1.0278 - 0.0278\ \times Reps)}.$$

The estimation accuracy of the repetition to failure method is better the closer the used load is to the actual 1RM, because relationship between muscle endurance and strength is curve linear in the higher set lengths (Fig. 9a). This set length is closely related to time to failure of working muscles and differences in metabolic demands of the repeated repetitions during the first 15 seconds (Fig. 9b). This method highlights the load-muscle endurance relationship to the detriment of velocity aspect, especially during longer set lengths when lower loads are used (Thorstensson & Karlsson, 1976).

a) b)

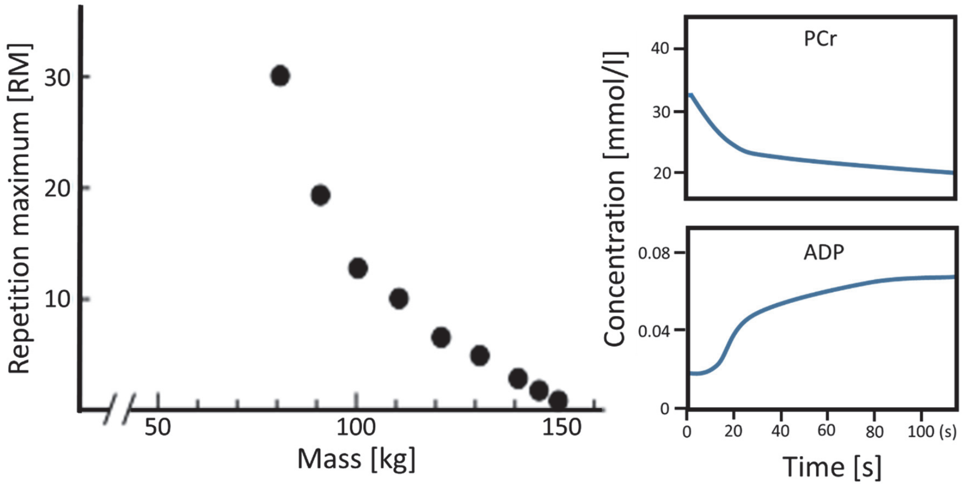

FIGURE 9. a) The relationship of endurance capability in repetition to failure sets. (Knuttgen & Komi 2003, pp. 7). b) The changes in phosphocreatine level (PCr) and oxidative phosphorylation (ADP) during exercise (Modified from Conley et al. 2001).

One possible modification to the repetition to failure test is to use two sets to failure, which approximates 1RM based on the sub-maximal strength profile. In this model, the weight of the first set should be around 5RM and the second 10RM. Formula for the two sets to failure test protocol is (Brzycki 2000) the following:

$$Predicted\ 1RM =$$

$$\left(\frac{Weight\ in\ the\ 1st\ set\ (kg) - Weight\ in\ the\ 2nd\ set\ (kg)}{Reps\ in\ the\ 2nd\ set - Reps\ in\ the\ 1st\ set} \times (Reps\ in\ the\ 1st\ set - 1)\right) +$$

$$Weight\ in\ the\ 1st\ set.$$

Inversely, when the load-repetition relationship is more linear, the repetitions to failure test may reflect the potential force producing capacity during the performance of a maximal load (Wilson 1992, pp. 1-15). If a person can perform more repetitions with chosen load than formula based presumption includes, it suggests that the maximal load is less than it should normally be in the reference group. However, the relationship between the lifted weight and repetitions to failure might change over time due to the used training program (Braith et al. 1993).

Load-velocity method. In some cases, performing submaximal repetitions to failure for the estimation of 1RM is problematic e.g. in cases when fatigue needs to be avoided. 1RM and thus maximum strength is also possible to evaluate from the load-velocity relationship. According to the study of Jidovtseff et al. (2011), which combined data from three different studies (Jidovtseff et al. 2008(a); 2008(b); 2009), average velocity represented the ability of the subject to lift the load and it decreased linearly with increasing load, at least in isoinertial condition (see also Fig. 11a).

$$\text{Predicted 1RM} = (0.871 \times TL0) - 0.624,$$

where TL0 is the theoretical load at 0 m/s (Jidovtseff et al. 2011).

The relationship between the lifted load and reached velocity correlated strongly in the cross-sectional study design, but longitudinal results and their accuracy are unknown (Jidovtseff et al. 2011). For example, the amount of the explosive strength deficit might change due to strength training e.g. the changes in muscle fiber type distribution, could have an effect on the ratio (explosive strength deficit) between potential maximum (F_{mm}) and trial specific maximum strength (F_m) (Zatsiorsky & Kraemer 2006, pp. 27):

$$\text{Explosive Strength Deficit (\%)} = 100 \times (F_{mm} - F_m) / F_{mm}.$$

2.4.1.2 Power strength evaluation

Typically, in sport, mechanical power and power generation is determined via kinetic and kinematic components, whose relationship is curvilinear. The theoretical model of Minetti (2002) showed that separate changes in muscle force or CSA lead to curvilinear relationships between duration, speed and power of contraction in *ceteris paribus* –condition (when all other things are equal). This theoretical model of Minetti (2002) is also extended to explain the effects of strength training and de-training (Zamporo et al. 2002). The classic study of Hill (1938) offers the often used equation to interpolate maximum power. Practical application of the Hill equation shows that the maximum power output occurs at around 1/3 of the maximal force in the isolated muscle. Interestingly, the study of Desmedt & Godaux (1977) observed that most of the motor units are recruited at this same force level (1/3 of maximum) during ballistic contraction. This force and velocity relationship is reported to follow (R^2 = 0.91-0.95) the hyperbolic model of Hill from muscle fascicle levels to single joint output (Hauraix et al. 2016). Furthermore, it has been also reported that in the single joint movement, peak power is reached at the load equal to 3–35% of maximal force (Toji & Kaneko 2007). In addition, sometimes it is necessary to approximate performance capacities at both ends of the force-velocity curve. Thus, Hill's equation can be used to extrapolate also muscle's maximum shortening velocity (F is 0) or maximum isometric force (F is max), although the recommended force range, for equation, is between 0.05-0.8 times maximal force (Seow 2013). Many applied studies have shown that peak power generation is reached in higher than 1/3 of maximum load, even up to near 80% of 1RM load, depending on the movement and training background (Garhammer 1993). However, e.g. strength-power trained athletes reached their peak power against their own body weight during counter movement jumps and their body mass was 35% from their 1RM back squat loads with added body mass (without shank mass) (Nuzzo et al. 2010). Hill's equation takes into account mainly the changes of single muscle length in the initial part of the movement (Matsumoto 1967), while continuous movement with co-acting muscles over several joints compose peak power in sport performances. It is well known, that power output during weightlifting (the snatch and the clean and jerk) and powerlifting (squat, bench press, and deadlift) decreases as the weight lifted increases and thus there is an inverse relationship between monitored power output and performed lifts (Garhammer 1993). In athletes, their training background and performance technique may play a role in the optimal load for power production, but also power production during close to maximal loads (Garhammer 1993). Several authors have shown that the shape of force-velocity curve is steeper in high strength subjects than low strength and the individual level of strength at the specific load could influence this relationship (Sale 1988; Hortobagyi & Katch 1990). Usually, force-velocity or power curves were created using peak values of movement or the part of the movement or at some specific joint angle. In addition, the dynamic rate of force or velocity development can be under of interests. However, the interpretation of these force or velocity development tests may be challenging, based on complex causation between the changes in force production, joint angle and time. In addition, the performance technique and the utilization of the stretch-shortening cycle can have an effect on power output, when the second lift is, typically, more powerful than the first one (Garhammer 1993).

Dynamic strength index (Young 1995) or dynamic strength deficit (Sheppard et al. 2011), which is based on the ratio between ballistic (dynamic) peak force and isometric peak force, represents the profile from a part of the force-velocity curve. This index compares maximal force production between a dynamic isoinertial condition with a specific load and the isometric end of the velocity curve in the lower (Sheppard et al. 2011) and upper body (Young et al. 2014; 2015). Conclusions from this ratio could be increasing maximum strength training if the index is e.g. the same or higher than 0.75 (Fig. 10a), but when index is less than 0.75 the training focus should be increasingly in the ability to generate maximal force at higher velocities if total maximal force is on adequate level (Fig. 10b).

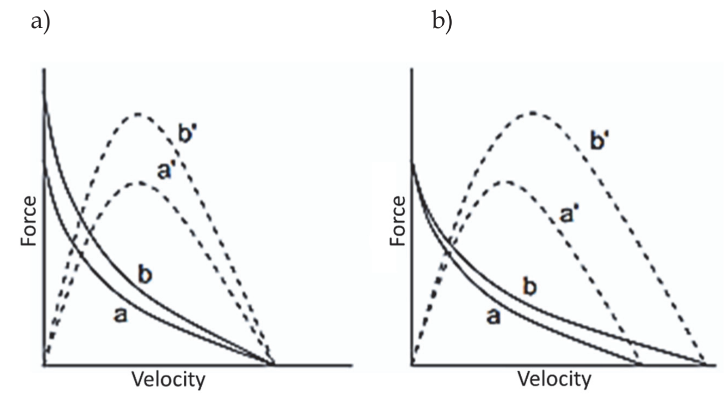

FIGURE 10. The effect of a) maximum strength training and b) high velocity training for power production (dashed line). In the figures, a is before and b is after training. (Frost et al. 2010).

Index workout. Repeated power training sets –test pattern for weight lifting requires the ability to maintain efficient muscle work during sets and gives information about recovery. This test pattern includes, for example, 5 sets of 10 repetitions with maximal effort and the rest period between sets is constant (e.g. 3 minutes). Measured variables are maximal concentric velocity and total power from each repetition and their changes between different repetitions and sets. Based on the information of this test, it is possible to tailor the athlete's training program towards an optimal amount of repetitions and /or sets using various loads e.g. for power training goals (Kauhanen 1998). One index workout model is the "Kansas Squat Test" or "KST", which includes 15 speed repetitions at 6-second intervals with 70% load from total 1RM (1RM + body mass) in a smith or leg press device. Followed performance variables are maximum power, mean power and relative decrease in power production due to fatigue. The KST with repetition power parameters might be a better method to measure lifting specific anaerobic endurance and the phosphagen system than e.g. a Wingate anaerobic test (Fry et al. 2014). Gorostiaga et al. (2014) observed that the decline in mechanical power output could be an indirect measure to estimate blood lactate and ammonia during exercises. Generally, these index workouts are strongly dependent on the stability of external conditions e.g. used exercise device or time from previous exercise session (Foster et al. 2017).

2.4.1.3 Hypertrophy evaluation by kinetic and kinematic variables

Body size (anthropometric differences) is quite complicated from a training monitoring perspective, because it is not clearly performance related. The relationship between anthropometric variables and maximum strength could be a model to predict body composition without submitting the subject to corresponding measurements e.g. ultrasound or DXA. However, this method is suitable only for large populations and produces only general approximations because, for example, chest and arm circumferences correlate only moderately ($r = 0.38$ to 0.45) to the 1RM result in the bench press (Ballmann et al. 1999; Scanlan et al. 1999).

Lean body mass or muscle cross-sectional area are slightly easier to use in training monitoring compared to total body size. The contraction force of a muscle and its' cross-sectional area are linked together, as maximal force production is around 40-100 N/cm2 (Andersson & Schultz 1979; Haxton 1944; Ikai & Fukunaga 1968). In general, this rough relationship is independent of age, gender or training background. Mechanically, muscle fiber composition and their architecture cause meaningful effects on contraction force. Naturally, also different neural components have to be taken into account, but e.g. recruitment of active motor units is more critical when monitoring the amount of hypertrophy compared to motor unit firing frequencies, which mainly fine tune force and velocity production. Therefore, moderate or relatively slow contraction velocity may offer an effective way to activate all motor units from slow to fast ones as a basis for the approximation. Isometric testing offers (usually) similar slow recruitment of all motor units compared to isoinertial resistance where faster recruitment is needed for the initial force impulse against the effect of inertia. This also minimizes the utilization of elastic components during the testing.

The approximation of CSA based on its correlation to maximum strength is not optimal, if the determination of the maximal strength is made only based on 1RM. Training with maximal load (1RM) has not been shown to increase muscle mass maximally. Muscle growth may be linked to the amount of repetitions or metabolic stress from some exceeded resistance level. For example, Mitchell et al. 2012 observed a similar increase in quadriceps volume between three sets to failure with 30% 1RM or 80% 1RM load after a 10-week resistance training period, when one set to failure with 80% 1RM load increased quadriceps volume only half of the other groups. Therefore, hypertrophic training type "maximum strength", such as 6-12RM, could be a more accurate method to evaluate the amount of muscle mass based on correlations with strength properties.

Volume of training load is one of the most typical strength training parameters monitored. A high-volume training program with hypertrophic training type enhances glycolytic activity, which has been linked to elevate e.g. acute anabolic hormone levels (e.g. testosterone) more than low-volume programs (Kraemer et al. 1990; 1991). The simplest method to calculate training volume is to simply multiply the number of sets and repetitions together, but the more typical and practical equation also takes into account the amount of used loads (Haff 2010):

$$Volume\ load = Number\ of\ sets \times Number\ of\ repetitions \times Load\ (kg)$$

or

$$Number\ of\ sets \times Number\ of\ repetitions \times (\%\ of\ 1RM \times 1RM).$$

Therefore, volume load is related to the mechanical work done during the exercise or session. In addition, when the amount of repetitions is replaced with actual lifting distance it is possible to determine the performed work or minimum energy for this volume equation. The testosterone effective high volume load equation should include 4 sets or more (Schwab et al. 1993). High volume load reflects maybe more a metabolic aspect of the hypertrophy, while training intensity highlights more tension and/or mechanical damage-induced stimuli of each repetition for muscle growth in the training program. Nevertheless, it is not clear whether the hypertrophic superiority of high volume load is the result of repeated and greater muscle tension and damage, metabolic stress, or some combination of these factors (Schoenfeld 2010). Training intensity can be calculated e.g. (McGuigan 2017):

$$Training\ intensity = Volume\ load\ (kg)\ /\ Total\ repetitions.$$

It is also possible to represent these absolute training volume and intensities by relative loads and/or related parameters to body weight and/or size (volume and intensity indexes). This approach would include trying to equalize the amount of training-induced stress between individuals or e.g. weight-class athletes during their weight loss periods (Haff 2010). However, the abovementioned training intensity parameters include less information compared to the training volume parameter, because the effect of repetitions is removed in the equations. In the SI system (System International d'Unites), the term "intensity" is established to quantify brightness of light as luminescence, which unit is candela [cd]. It is closely, but not exactly, related to $W \times m^{-2}$ unit (Winter et al. 2015) and e.g. power production or sustained isometric force production (against gravity with the function of time) during each repetition and set (Knuttgen & Kraemer 1987; Komi 2003, pp. XIII). Therefore, the term "training intensity" should be re-determined to include also the time component, after the commissioning of near future strength training monitoring technologies. This could enable a new approach for more accurate "intensity" ranges and target zones for specific exercise or loading-goals (e.g. hypertrophic, maximum strength or power strength) compared to current intensity domains; "moderate", "heavy", "very heavy", "severe" and "extreme" (Whipp 1996, pp. 83; Herda & Cramer 2016). Nevertheless, the amount of the training intensity (estimated by any method) is not so unambiguous at the moment or beyond the point of momentary muscular failure e.g. the final repetition cannot be fully completed due to fatigue or forced repetitions applied, or cheating, etc. (Giessing et al. 2005).

In strength training, total intensity during an exercise, a single session or microcycle is termed sometimes "density", referring to frequency of training (Bompa & Haff 2009, pp. 81). Therefore, the density term includes also rest periods between work phases. Optimal density is difficult to calculate, because an athlete's recovery rate is the sum of several factors e.g. training status and chronological age. One example equation for absolute density (modified from Bompa & Haff (2009, pp. 95) is as follows:

$$\textit{Absolute density} = (\textit{Absolute training time} - \textit{Sum of rest times in session}) \times 100 \,/\, \textit{Absolute training time},$$

where Absolute training time is the total duration of training session.

This balance between working and recovery phases of training could also be presented via work-to-rest ratio, which is linked to average work time, % of maximum power and targeted energy system during strength training (Herda & Cramer 2016). Work-to-rest ratios are e.g.

Typical work time 5-10 s with 90-100% power and phosphagen => ratio is 1:12-1:20,

Typical work time 15-30 s with 75-90% power and fast glycolysis => ratio is 1:3-1:5,

whereas ratios of 1:12-1:20 target strength- and power-generating characteristics and 1:3-1:5 target the development of hypertrophic characteristics (Bompa & Haff 2009, pp. 94).

The foundation for monitoring based periodized strength training plans is the manipulation of training volume, intensity and density. Generally, these variables are closely linked to muscular time-under- tension in dynamic training, but the muscular time-under-tension and the percentage of effort are also common features between dynamic and isometric muscle contractions. In nearly similar contraction levels (70% or higher from MVC), as in hypertrophic training type (6-12RM), blood circulation is prevented during sustained isometric condition (Lind et al. 1964), which can lead to utilization of anaerobic metabolism and, thus, acidification into the muscles, similar to hypertrophic training itself. Therefore, it is reasonable to speculate whether the area under the force-time curve could be (at least moderately) related to the size of the lean muscle mass in the agonist muscles, although skeletal muscle fatigue might differ between contraction modes (Allen et al. 2008).

2.4.2 Isometric parameters in monitoring of strength training

In an isometric condition, force or torque is produced against an immovable resistance at a specific joint angle, and it only represents isometric strength level at a narrow range about that specific joint angle (Fig. 11). However, Yates & Kamon (1983) showed that measured torque production at a constant angle is more sensitive to e.g. influences produced by muscle fiber type rather than angle independent peak torque during dynamic contractions. Isometric tests are easily standardized, they require minimal familiarization and are safe to perform maximally also during fatigue (Blazevich & Cannavan, 2007, pp. 130). However, dynamic and isometric strength levels were not interchangeable based on differences in function of neural activation and muscle-tendon units (Nakazawa et al. 1993; Blazevich & Cannavan 2007, pp. 130).

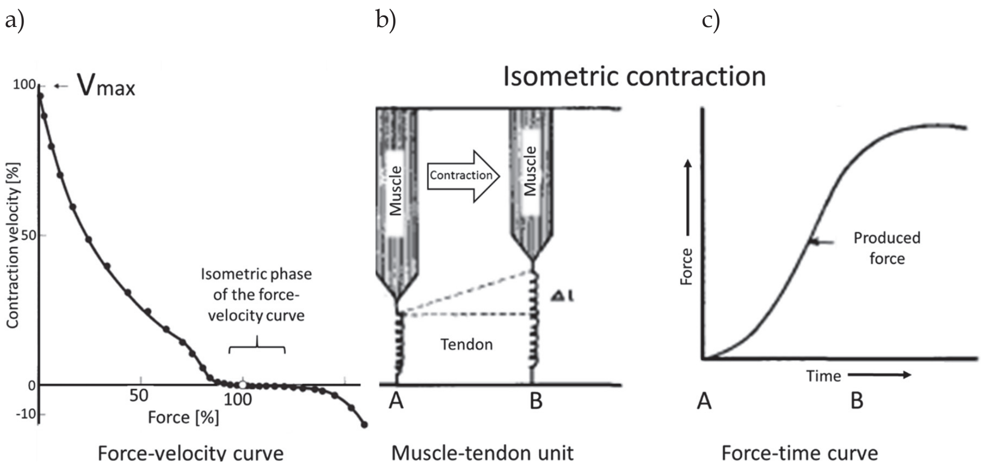

FIGURE 11. a) Force-velocity curve, b) muscle-tendon unit during isometric contraction, c) force-time curve (Komi 1974).

2.4.2.1 Maximal Voluntary Contraction (MVC)

At the moment of maximal isometric force/torque production, parallel elastic components of the muscle-tendon complex are maximally stretched and contracting force is transferred (Fig. 11b-c). Theoretically, concentric force production (positive work) at the same joint angle is lower than isometric force, because concentric force production needs to exceed the resistance for the velocity of the movement. The figures 11a,c and 12 represent the force-end of the dynamic force-velocity curve compared to the force-time curve of isometric maximal contraction. (The eccentric condition will not be discussed in this thesis). However, the ability to exert both dynamic and isometric peak force still shares some functional and structural similarities with the ability to generate force (Fig. 13a,b) and, thus, several studies have found a strong relationship between isometric peak force and 1RM (Fig. 12) (Schmidtbleicher 1992; Haff et al. 1997). On the other hand, there are other studies that have reported that isometric MVC is not necessarily related to dynamic 1RM (Baker et al. 1994). Although, Yates & Kamon (1983) observed that the optimal muscle length and thus joint angle for maximal force is independent of the strength level or muscle fiber composition.

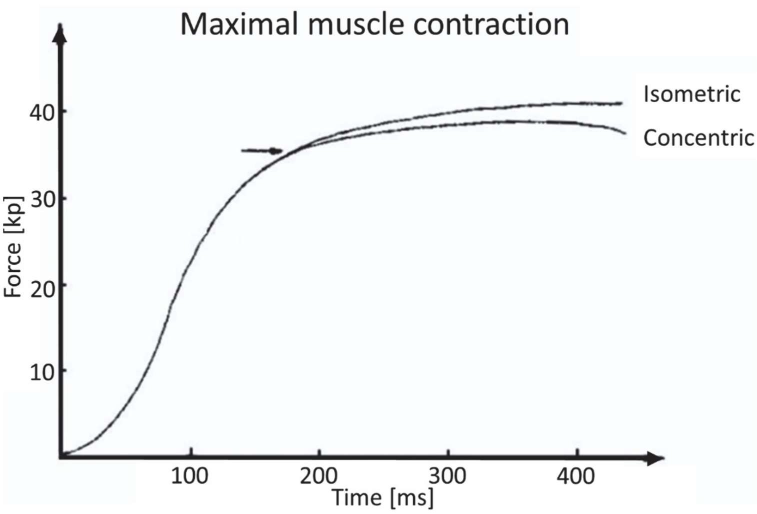

FIGURE 12. Maximal force-time curves during concentric and isometric contractions (Modified from Schmidtbleicher 2003.)

Balshaw et al. (2016; 2017) determined that the changes in MVC were explained by ~60% with pre-training MVC, the volume and EMG of agonist muscles of the pooled subjects after explosive and sustained-contraction isometric strength training. Specifically, the improvement of the EMG in the agonist muscles alone explained ~30% of the improved MVC, which might be related to increased firing rate and recruitment of motor units (Sale 2003, Fig. 13 c,d). The parameters of the "best fit" models for predicting isometric (R^2=0.72) and dynamic strength R^2=0.72 (R^2=0.66) included in both models the CSAs and the fascicle angles of the agonist muscles (Trezise et al. 2016). In addition, the accurate concentric model was completed with moment arm values and the isometric model with EMG and voluntary activation values. However, the accuracy of the "best fit" concentric model was similar with or without the EMG parameter, and CSA was the main individual predictor parameter to explain maximal strength (R^2=0.46-0.59). The "best fit" models for maximum isometric and concentric strength predictions (Trezise et al. 2016):

$$\textit{Isometric strength} = 3.24 \times (CSA) + 427.29 \times (EMG) + 3.16 \times (\textit{fascicle angle}) + 2.93 \times (\textit{voluntary activation}) - 290.05 \qquad (R^2{=}0.72)$$

$$\textit{Concentric strength} = 2.34 \times (CSA) + 2.12 \times (\textit{fascicle angle}) + 2.74 \times (\textit{moment arm}) - 126.81. \qquad (R^2{=}0.65)$$

In fact, these parameters consisted of other "sub" factors, as CSA, which might be linked to the differences in e.g. calcium sensitivity, fascicle length and angle and metabolism. On the other hand, the binominal role of EMG might be explained by e.g. differences in pre-activity pattern, recruitment threshold, as well as firing frequencies between isometric and concentric contractions (Linnamo et al. 2003; Murphy & Wilson 1996; Kay et al. 2000). Although, the relationship between MVC and 1RM is questionable and certainly more research is needed, the between-session reliability of MVC is strong (within-subject coefficient of variation is 3.3% and intraclass correlation coefficient is 0.95; Buckthorpe et al. 2012) which creates a basis for its use in monitoring after detailed research.

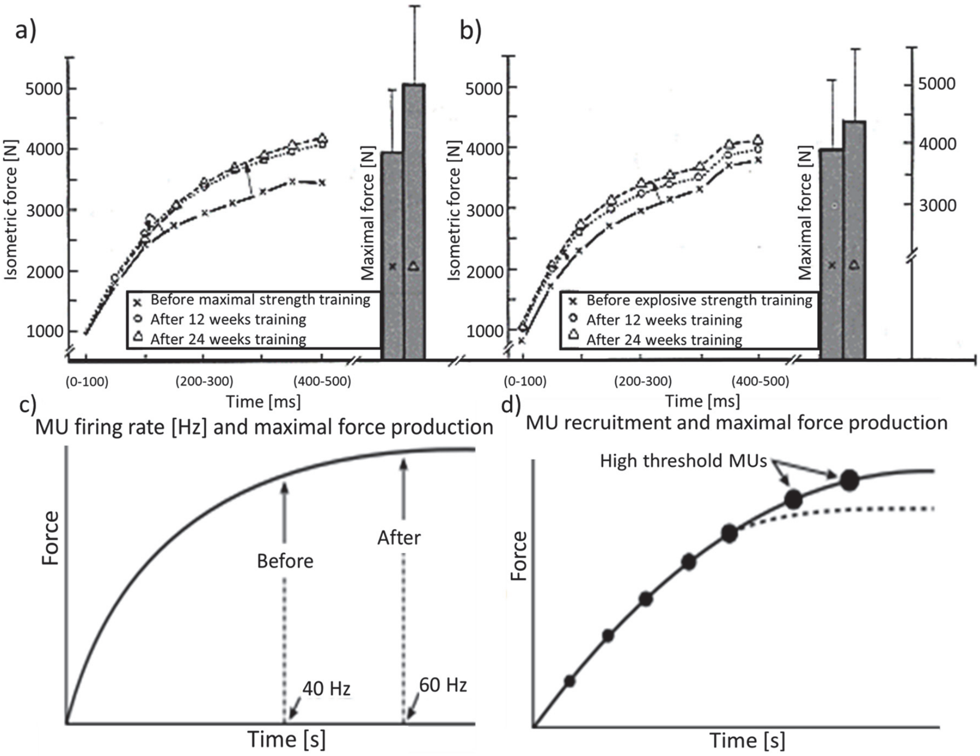

FIGURE 13. The changes in force-time curve and maximal force due to a) maximal strength training and b) explosive strength training (Modified from Häkkinen et al. 1985a, 1985b). The changes in maximal force production due to increased c) firing rate and d) recruitment of motor units (MU) due to maximum strength training (Modified from Sale 2003, pp. 283).

Hornsby et al. (2017) showed that the changes in MVC due to strength training are much smaller in magnitude compared to RFD. In addition, Hornsby et al. (2017) observed that MVC is less sensitive than RFD to training variable alterations among advanced strength-power athletes. However, the changes of magnitudes in these parameters were depended on the type of the strength training and the phase of periodization (Hornsby et al. 2013; 2017). Several authors have reported that modifications in the loads of the training volume and/or tapering has been proposed to bring forth performance capabilities (e.g. Storey et al. 2016) and the improvements of isometric force production (e.g. Zaras et al. 2014) in athletes.

2.4.2.2 Rate of Force Development (RFD)

The ascending part of isometric force-time (or torque-time with moment arm; RTD) curve during fast maximal contraction is often determined to characterize explosive strength capacities of different individuals. The produced force per time unit and area beneath the force-time curve (Impulse) or force level reached during a specific time span are typical parameters in the laboratory environment. However, in several studies, moderate to strong correlations between isometric and dynamic force-time characteristics were observed (Haff et al. 1997; 2005; McGuigan et al. 2008). Specifically, maximal concentric acceleration against weight (and inertia) and isometric fast force production seems to behave more and more similarly due to a steeper and steeper part of the force-time curve in the beginning phase of the contraction. (Fig. 14). The training, which includes concentric explosive force production, realizes to reach peak forces in the beginning of the movement related to the time (10 ± 30 ms) or distance (0.3 ± 1.9%) from the onset of contraction (Newton et al. 1996) (Fig. 15c). In addition, the study of Newton et al. (1997) with explosive force production during stretch-shortening cycle actions showed that the peak force occurred at the isometric moment, when the eccentric phase turns to concentric movements. Nevertheless, the role of the elastic structures is impossible to exclude in stretch-shortening cycle movements. However, already Godik & Zatsiorsky (1965) showed, that the time to peak force is not depend on the initial force level in isometric condition. In addition, the muscle-tendon unit stiffness is not independently related to fast force production during explosive isometric contractions (Hannah & Folland 2014).

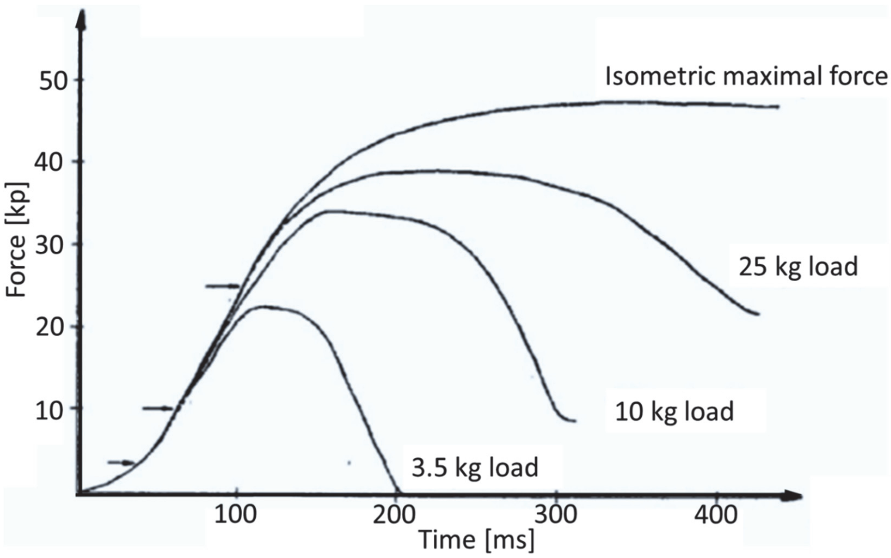

FIGURE 14. Maximal isometric force-time curve compared to dynamic contractions with different loads (Modified from Buhrle & Schmidtbleicher 1981).

In determination of RFD, a relatively wide time window is more related to MVC compared to narrow ones (Aagaard et al. 2002). In some cases, the fast force production is normalized to MVC, which should highlight, specifically, the relative changes of fast force production, with the minimal effect of maximum strength. However, this might be questionable in strength training intervention follow-ups, because the changes in these parameters represent different aspects of the neuromuscular system. For example, muscle fiber conduction velocities correlated stronger with RFD (at the first 100ms-250ms), than MVC parameters (r=0.85-0.92 vs. r=0.66) (Methenitis et al. 2016b). In addition, previous studies have observed that the isometric RFD is influenced by several neural adaptations (Fig. 15a-c), but also mechanical and architectural factors (Andersen and Aagaard 2006; Blazevich et al. 2009; Bojsen-Moller et al. 2005; DeRuiter et al. 2004). Reliability of RFD is associated with the time phase of the force-time curve. Previous studies have observed that between-session reliability increases with increasing width of the analyses window after force onset (within-subject coefficient of variation between 0-50 ms is 12.8-16.6%; 0-100ms 4.5-5.3%; 0-150 ms 4.5-5.1%) (Buckthorpe et al. 2012; Tillin et al. 2011).

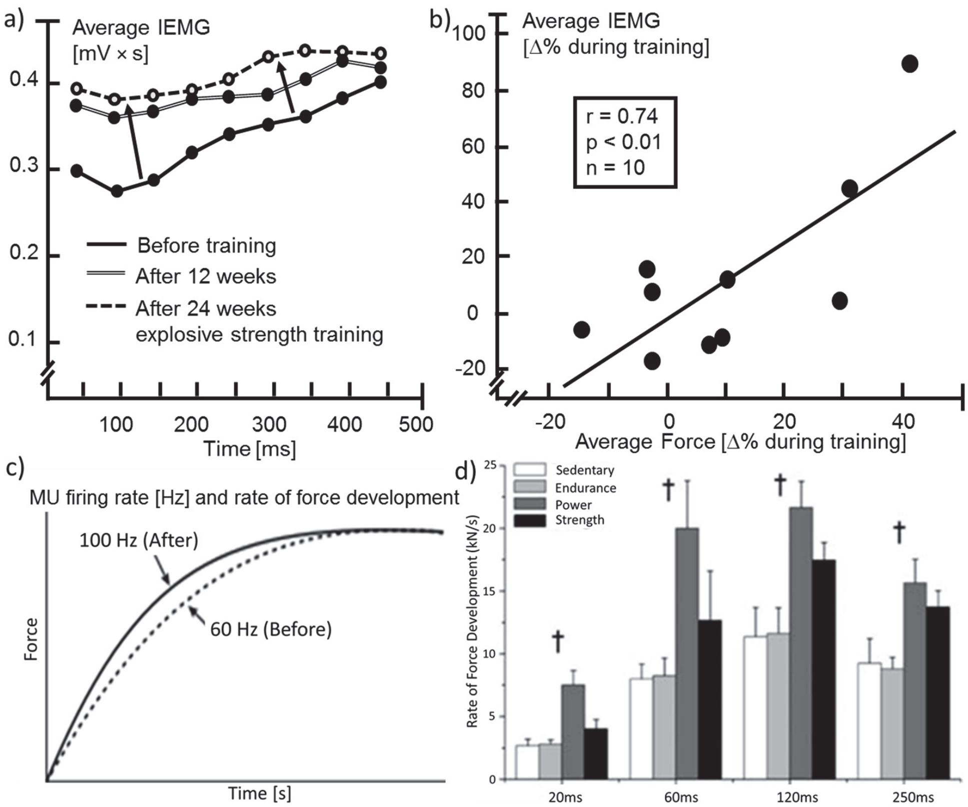

FIGURE 15. The changes in a) average IEMG during explosive isometric contraction and b) the correlation between IEMG and force production due to explosive strength training (Modified from Häkkinen et al. 1985 a, 1985b). c) The changes in rate of force development due to increased firing frequency of motor units (MU) due to explosive strength training (Modified from Sale 2003, pp. 283). d) Isometric leg extension RFD among sedentary individuals, endurance runners, and power- and strength-trained athletes (Modified from Methenitis et al. 2016a).

3 PURPOSE OF THE STUDY

In strength training, it is highly challenging to measure, quantify and follow systematically all different acute and chronic responses affecting a trainee and to assess how the individuals have adapted to the stimuli in order to determine a follow-up output response. However, it would be fair to assume that kinetic and/or kinematic outputs of any strength exercise sum up the effects of physiological, biomechanical, psychological, technical performance and health-related variables and, thus, offers potential windows for training monitoring (Smith 2003). At the same time, increasing scientific knowledge about the physiology behind strength training and technical revolution with cost- and time-effective processors creates huge potential for monitoring the strength training responses and adaptations. In the field, or in this case rather in the gym, frequent and systematic monitoring should be based on repeatable, easy, and inexpensive in-vivo measurement parameters, minimizing disturbance of a current training session. Modern strength training is typically based on dynamic type training, but commercial training devices utilize several resistance modes e.g. weight, pneumatic or elastic based resistances. The effects of training specificity have been shown in several studies; thus, isometric variables could be a valid option for monitoring strength training, independently of the dynamic resistance modes. In addition, isometric tests are very repeatable, relatively inexpensive and easy to use, and isometric tests cause less fatigue than other contraction modes and, thus disturb a training session less. Naturally, isometric tests do not include the effect of inertia, while most sport and daily activities do.

The specific aims of the present thesis are outlined as follows:

1) The first part of thesis compares the qualities of the two most widespread resistances during single repetitions and acute neuromuscular responses after different strength training loadings with these resistance modes (original paper I). Thus, the specific aims are:

   a) To evaluate the ability of different feasible monitoring parameters to identify specifically maximum strength, power and hypertrophic loading-induced fatigue.

   b) To determine common and distinct characteristics of these parameters between the different resistances with or without inertia.

2) The second part of thesis compares the effect of modified inertia based resistances during explosive movements in unfatigued and fatigued conditions, as well as acute neuromuscular, kinetic and kinematic responses after power type loading (original paper II). Therefore, the specific aims are:

   a) To determine the effects of inertia modified resistance on kinetic and kinematic parameters during power loading.

   b) To evaluate differences in power loading-induced neuromuscular fatigue and recovery based on selected isometric parameters.

3) The third part of thesis compares adaptations due to strength training with inertia based resistance devices to isometric monitoring data via selected parameters identified in the first and the second parts of thesis (original paper III). The specific aims are:

   a) To evaluate the ability of the selected isometric parameters to reflect different chronic neuromuscular adaptations due to strength training.

   b) To compare training-induced neuromuscular adaptations and the changes in performances between hypertrophic and maximum strength followed by power training type resistance training.

4) The fourth part of thesis determines whether acute training responses and chronic neuromuscular adaptations explain differences between individuals in the timing of the improvement in rate of force development parameters during maximum strength followed by power training periods (original paper IV).

Therefore, the 1st and 2nd experiments of this thesis focused on the acute changes in different neuromuscular fatigue-indicating parameters during typical strength loading types related to the effect of inertia; a) to responses with minimal inertia via pneumatic resistance, b) typical inertia via weight based resistance and c) elastic band compromised weight based resistance in the cross-sectional study design. Based on the analysis of the results of the experiments 1 and 2, isometric maximal voluntary contraction (MVC) and the steepest 10 ms window of the isometric force-time curve (peak RFD) and time to reach peak RFD were defined as follow-up parameters for strength training monitoring in intervention experiments.

The cross-sectional study designs showed that the weight-stack resistance-joint angle –curve was able to produce variable stress to the neuromuscular system throughout the movement based on the weight used and velocity obtained during single repetitions. Therefore, the manipulated volume, intensities and densities during hypertrophic, maximum strength and power strength sessions induced multifaceted, but loading-specific neuromuscular fatigue. Thus, these loading specific fatigue effects may also cause training specific stimuli and adaptations due to the training intervention for the testing of the chosen monitoring variables. Therefore, experiment 3 included two groups with different strength training programs, a) hypertrophic type training with a muscular growth focus and b) maximum strength and power type training with neural and peripheral focuses, from which chronic adaptations were followed by isometric monitoring tests. Experiment 4 investigated individual differences in the improvements of force production and reasons behind these adaptations due to maximum strength and power type training.

4 METHODS

4.1 Subjects

A total of 69 men participated in these studies. The age range of subjects was 20-35 years and they were healthy and physically active (experiment specific anthropometric data in Table 2). None of the subjects had previously taken part in any systematic strength training program, which would include more than once per week training frequency. Otherwise, all the subjects were physically active and took part in recreational physical activities for a few hours per week (endurance or ball games activity took place no more than 2 times per week). Subjects in the control group were instructed to maintain their normal living and physical activities during the corresponding intervention time between the pre- and post-measurements in the laboratory.

All subjects were recruited through advertisements. The exclusion criteria included cardiovascular diseases, impaired musculoskeletal and /or endocrine functions, or any other condition that may have restrained performing the testing or training protocols. Each selected subject was carefully informed of all potential risks and discomforts and, thereafter they singed an informed consent document. The study was conducted according to the declaration of Helsinki, and ethical approval was granted by the ethical committees of the University of Jyväskylä and the Central hospital of Jyväskylä, Finland.

TABLE 2 Summary of the physical characteristics of the subject groups during each experiment (Exp.) and original papers (mean ± SD).

	Exp. No	n	Age (years)	Height (cm)	Body mass (kg)	Orginal paper
Cross-sectional studies	1.	16	30 ± 4	179 ± 7	77 ± 8	I
	2.	15	28 ± 5	181 ± 4	79 ± 10	II
Longitudinal studies	3.	14 (HYP)	27 ± 5	177 ± 6	71 ± 8	III
		14 (MSP)	30 ± 4	178 ± 4	79 ± 4	III
		10 (C)	30 ± 4	180 ± 6	84 ± 14	III
	4.	14 (MSP)	30 ± 4	178 ± 4	79 ± 4	IV

4.2 Structure of experimental design

Altogether four separate experiments were performed. Cross-sectional experiments 1 and 2 resulted in original articles I and II. Experiment 3 and 4 were built into the same resistance training intervention, which resulted in original articles III and IV. In the order of study in the thesis (Fig. 16), the follow-up monitoring parameters of the resistance training intervention (longitudinal experiments 3 and 4) were determined during loadings in the cross-sectional experiments 1 and 2. The present thesis primarily focused on the usability and sensitivity of potential monitoring parameters to reflect specific characteristics of fatigue due to each loading types and resistance modes were compared to more sophisticated laboratory tests. The secondary aims of the thesis were determined as (1) the acute effects of weigh-stack and pneumatic resistances with specific loadings (power, maximum strength, and hypertrophic), (2) single-repetition performances and loading-induced fatigue due to weight-stack with and without elastic resistance, (3) strength training monitoring during a long-term intervention and (4) individual strength training responses based on isometric rate of force development.

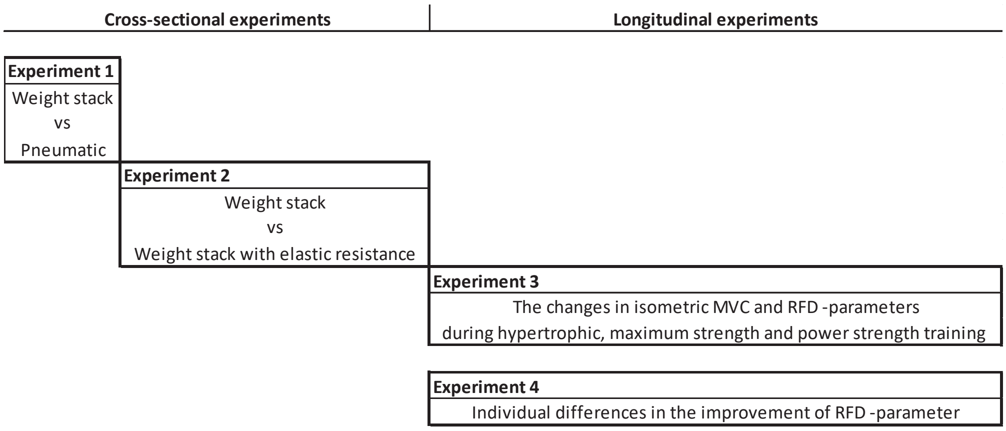

FIGURE 16. The experiments ordered by time in the thesis.

4.2.1 Experiment 1

The first experimental design compared single repetitions with different loads and the acute effects of power, maximum strength and hypertrophic loadings due to pneumatic and weight-stack based resistance devices, because limited scientific attention has been focused on properties and functions of the different resistance modes. Inertia is linked to a mass and force that is produced against it and thus it is involved in all movements in our daily life, however, the effects of reduced inertia during and after different resistance loadings is still unknown. The acute effects of these loadings were investigated using knee extension devices. As neuromuscular demands may be different between specific resistance loadings and, thus, the contribution of central and peripheral fatigue might be different as well, it was of interest to examine the fatigue contribution and the changes in kinetic variables and muscle activity due to these typical loadings (Fig. 17 and Table 1).

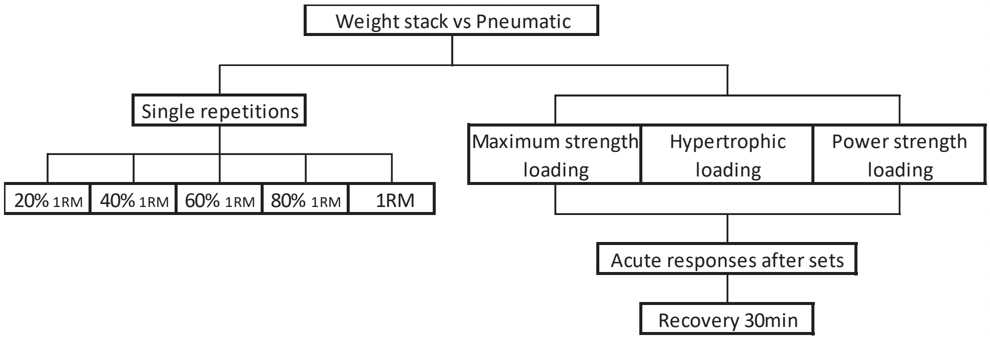

FIGURE 17. The comparison study design between pneumatic and weight-stack resistances in experiment 1.

4.2.2 Experiment 2

In resistance training, the effect of inertia is highlighted during acceleration and deceleration phase of contraction during power loading, thus, our research group modified inertia-based weight-stack resistance with an additional elastic band. This combination utilized the benefits of weight-stack resistance during the acceleration phase and progressively increased resistance via the additional elastic band toward the end of concentric contraction. In experiment 2, power loading was repeated with the same exercise variables as in experiment 1, but the test pattern and settings included more sophisticated measurements to detect the state of the neuromuscular system (Fig. 18 and Table 1).

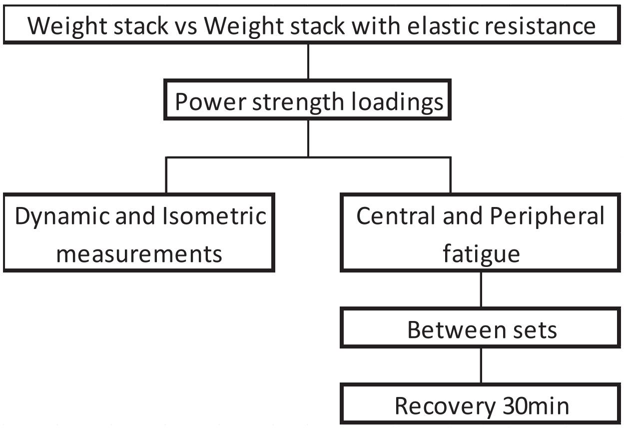

FIGURE 18. The comparison study design between weight-stack with and without elastic resistance in experiment 2.

4.2.3 Experiment 3

A 20-week weight-stack resistance training intervention was monitored by MVC and RFD parameters from isometric dynamometer measurements. The selection of these parameters was based on the previous cross-sectional studies (experiments 1 and 2). Two different training programs consisted of a periodized 10-week maximum strength training followed by 10-week power training with the greater neural focus compared to two 10-weeks hypertrophic periods with more emphasis on muscular growth. Both 10-week periods of hypertrophic type training were similar but used progressively increased loads, therefore greater volume load was achieved in the second 10-week period (more details in Table 2). Supervised whole-body training was performed twice per week throughout all training periods. In the gym environment, the effectiveness of subject's trainings was monitored using an isometric leg extension dynamometer with MVC and RFD parameters in the beginning of every 7th training sessions and also as part of the laboratory tests before, after 10 and 20 weeks of strength training (Fig. 19 and Table 1). The changes of the monitoring parameters were compared to the changes of the training specific parameters (muscle cross-sectional area, 1RM, acceleration, peak velocity).

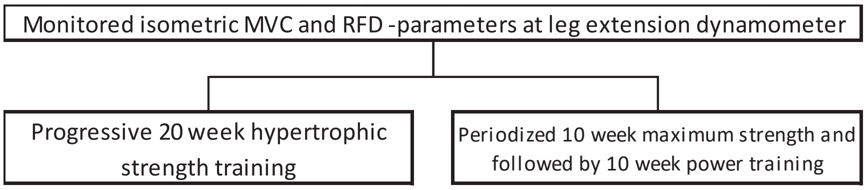

FIGURE 19. Study design in the experiment 3.

4.2.4 Experiment 4

Individual improvements in RFD during maximal bilateral isometric leg extension voluntary contractions due to periodized maximum strength and power training was monitored every 7th training session as in experiment 3. Afterwards, subjects were divided into three responder-groups based on their timing of improvement in RFD; 1) improved during maximum strength training, but only maintained during power training (Maximum strength-responders; MS), 2) improved only during power training (Power-responders; P) and 3) no improvement (Non-responders; Non) (Fig. 20 and Table 1).

The study design included isometric monitoring measurements with fingertip blood lactate for daily basal level and exercise-induced acute responses during every 7th training session before and after the leg press exercise, which was the first exercise in the session. In addition, pre-training levels and the changes in strength levels, muscle cross-sectional areas, electrical stimulation assessed force responses, hormonal status and other hematological values due to training were compared between responder-groups.

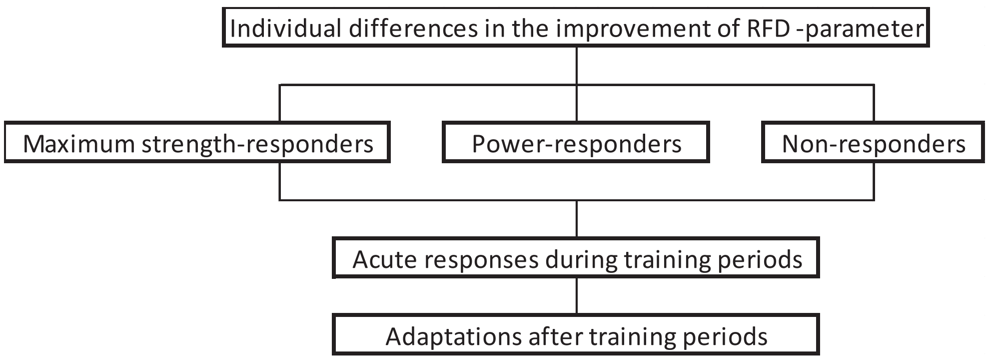

FIGURE 20. Study design in experiment 4.

TABLE 1 Summary of the study designs of each experiment, primary variables and original papers.

Exp. No	Experimental design	Performance	Primary variables	Original paper
1.	Pneumatic vs. weight stack resistance			
	a) Single repetitions 20, 40, 60 80 and 100%1RM	Knee extension	1) Concentric torque, velocity and power 2) Concentric muscle activity	I
	b) Loadings -maximum strength -hypertrophic -power	Knee extension	1) Isometric force parameters 2) Responses to muscle stimulation 3) Isometric muscle activity	
	c) Recovery		1) Responses to electrical muscle stimulation 2) Blood lactate 3) Isometric RFD	
2.	Pure weight stack vs. weight stack with elastic resistance			
	a) Single repetitions in the begining and the end of the loadinings	Knee extension	1) Concentric torque, velocity and power 2) Concentric muscle activity	II
	b) Loadinings -power	Knee extension	1) Isometric torgue parameters 2) Responses to nerve stimulation 3) Isometric muscle activity	
	c) Recovery		1) Responses to electrical nerve stimulation 2) Blood lactate	
3.	Strength training (20-week) -hypertrophic (20wk) vs. -maximum strength (10wk) and power (10wk) training	Whole body	1) Isometric force parameters 2) Concentric force, velocity and power 3) Concentric and isometric muscle activity 4) Responses to electrical muscle stimulation 5) Muscle hypertrophy	III
4.	Maximum strength (10wk) and power (10wk) training -individual RFD improvements a) Training adaptations b) Acute leg press loadinings every 7th training sessions	Whole body	1) Isometric force parameters 2) Concentric force, velocity and power 3) Concentric and isometric muscle activity 4) Responses to electrical muscle stimulation 5) Muscle hypertrophy 6) Serum hormone responses	IV

4.3 Cross-sectional experiments

Experiments 1 and 2 investigated acute loading-induced effects during and after maximum strength, power and hypertrophic loadings with different resistance modes using knee extension devices. Weight-stack resistance is composed almost entirely of mass, and is thereby influenced by inertia and momentum, while pneumatic resistance (experiment 1) is proportional to the air pressure in the cylinder and can be modified by lever arms of the structure, whereas the device frame provides only a minimal contribution to the total resistance. In experiment 2, the additional elastic band attached to weight-stack resistance compensates for the effects of inertia and momentum, and thus balances total resistance through to movement during explosive power actions, especially with low weights.

Loadings were performed using pneumatic (Hur 3350; Hur Ltd. Kokkola, Finland; in experiment 1) and weight-stack (David 200; David Health Solution Ltd., Helsinki, Finland; in experiment 1 and 2) knee extension devices. Experiment 2 combined resistance modes, an elastic band [circumference: 2,080 mm, width: 30 mm, thickness: 5 mm, and color: blue; details McMaster et al. (2010)] was attached to the weight-stack with the same load that was used without the elastic band (40% 1RM). The used elastic band attachment allowed the same resistance at the beginning of the movement, because the elastic band was tightened to begin resisting the movement after 10° knee joint angle extension. The full range of knee extension was 60-180°. The elastic band was chosen from commercially available training bands based on its stiffness qualities. For power training, the chosen elastic band is probably one of the most suitable to govern the inertial properties of the weight-stack. For that reason, it was not our intention to match the mechanical loading between these two conditions after the 70° knee joint angle when the elastic band resisted the movement.

Familiarization session. The first visit of the subject in the laboratory after recruitment included familiarization. In these sessions, the anthropometric data of the subjects were measured, and each device was set up according to individual anatomical dimensions of every subject. Surface electromyography (EMG) placements were measured and marked by indelible ink tattoos. In addition, submaximal electrical muscle and nerve stimulation (only in experiment 2) was performed to familiarize the subjects with these testing procedures. The subjects practiced maximum unilateral isometric knee extension trials and they performed a few repetitions with the bilateral loading devices before the determination of 1RM with correct instructions and verbal encouragements. In experiment 1, 1RM was determined separately in the weight-stack and pneumatic devices and, in addition, the familiarization session included explosive repetitions with 20%, 40%, 60% and, 80% loads on both resistance modes. In experiment 2, the 1RM was determined only for weight-stack resistance. The range of the dynamic knee (experiments 1 and 2) and leg extension (experiments 3 and 4) tests for knee joint was from 60 to 180°, and back support was set to 110° from the horizontal plane. After the familiarization session, subjects recovered at least 4 days before the next loading (experiment 1 and 2) or test (experiment 3 and 4).

Preparation for the loading sessions. All loading and measurement sessions took place at the same time of day (±1 hour) throughout the experiment, times were allocated to each subject individually and testing was performed throughout the day. The order of the loadings was completely randomized. These loading sessions were separated by 7 days and subjects avoided exercise 48 hours prior to tests. Subjects were also instructed to avoid alcohol consumption for 48 hours and to consume 0.5 L water 1 hour before they arrived to each loading, as hydration status has been shown to affect strength levels (Judelson et al. 2007). In addition, subjects fasted for 3 hours before loadings. In every loading session, subjects performed a warm-up, which consisted of 6 self-paced bilateral knee extension repetitions at 40% 1 RM on the loading device.

4.3.1 Maximum strength loading protocol

The maximum strength loading protocol (paper I) consisted of 15 sets of one repetition at 100% 1RM, with a 3-min rest period between the sets (Fig. 22). The pre-determined 1RM load from the familiarization session were was used in the first set, if the repetition was successfully performed to full knee extension then the next repetition was lifted at slightly (2.5-5 kg) higher load. If the subject could not voluntarily lift the load to full knee extension, an experienced trainer encouraged verbally and assisted to complete the repetition with maximal effort still coming from the subject and then the trainer reduced the load for the next repetition.

4.3.2 Power loading protocol

The power loading protocol (paper I, Fig. 22 and II, Fig. 21) consisted of 5 sets of 5 repetitions at 40% of pre-determined 1RM load, with a 3-min recovery. Each concentric repetition was performed as fast as possible, and the ankle pad was stopped after it was "kicked" before the subject performed controlled eccentric action. The load (40% 1RM) was constant during all sets and all power loadings.

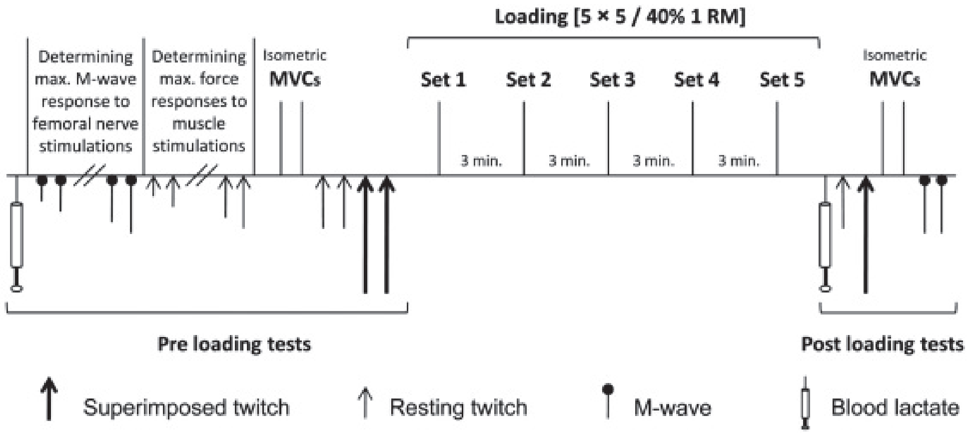

FIGURE 21. Power strength loading protocol in experiment 2.

4.3.3 Hypertrophic loading protocol

The hypertrophic protocol (experiment 1) was 5 sets of 10 repetitions at 80% 1RM, with a 2-min recovery (Fig. 22). During these hypertrophic loadings the subject was just able to finish the required repetition of each set and the knee extension sets were done using a self-selected (experiment 1) or metronome (2 sec concentric and 2 sec eccentric contractions) controlled tempo (experiment 2) with verbal feedback from an experienced trainer. In the first set, 80% of the pre-determined 1RM load was used; if the set was successfully performed to full knee extensions then the next set was performed with a slightly higher load. If the subject could not voluntarily perform the whole set, an experienced trainer assisted to complete the repetitions in the set while the subject still maintained maximal effort. Afterwards, the loads where then reduced for the following set.

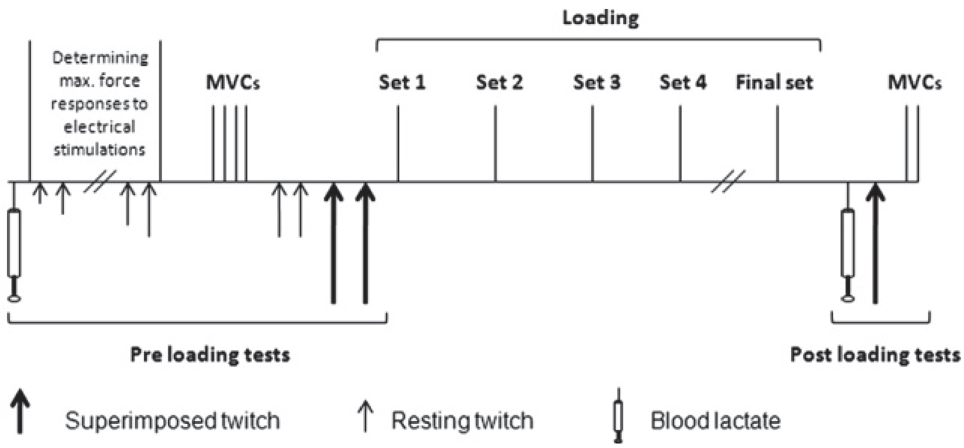

FIGURE 22. Hypertrophic (5×10RM/2min), maximum strength (15×1RM/3min) and power strength (5×5×40% 1RM/3min) loading protocols in the experiment 1.

4.4 Longitudinal experiments

The resistance training intervention included a 20-week hypertrophic (HYP) training (in experiment 3) or periodized 10-week maximum strength training (MS) followed by 10-week power (P) training (in experiments 3 and 4) period. The purpose was to identify both neuromuscular and hormonal adaptations, and improvements in performances due to targeted strength training, which were similar as the targets of the loadings (i.e. maximum strength, hypertrophy, and power) in the cross-sectional experiments. Training of both programs was performed twice per week and every training session included a combination of 8-9 exercises in all major muscle groups. Bilateral leg press, knee extension and knee flexion exercises were performed in every training session and before the other possible muscle exercises, such as bench press, shoulder press, seated row, lateral pulldown, triceps pushdown, biceps curl, back raises and abdominal crunches. The isometric monitoring tests were performed at the beginning (in experiments 3 and 4) of every 7th training session and after leg press sets, which was the first exercise in the session, with accompanying fingertip blood samples (in experiment 4). In addition, the same isometric test protocol and device with concomitant EMG recordings were used at the beginning of the laboratory tests before, and after 10 and 20 weeks of training. The familiarization (before the first laboratory test) and preparation protocols before all laboratory tests were similar in the longitudinal and cross-sectional experiments.

Moreover, experiments 3 and 4 included dynamic bilateral leg press (David 210; David Health Solution Ltd., Helsinki, Finland) performances of 1RM and single explosive repetitions at 50% 1RM load with EMG, as well as isometric knee extension and EMG combined with the interpolated twitch technique (ITT) to calculate activation level (AL) and the determination of cross-sectional area of m.vastus lateralis before, after 10 and 20 weeks of resistance training. The laboratory measurements included also basal blood samples and the determination of body composition for individual subjects. These were performed at the same time of the morning (after a 12 h fast) during the intervention to control for diurnal variation (Sedliak et al. 2007)

HYP training was split into two identical and progressive 10-week periods (HYP I and HYP II), where the relative intensity remained the same, but the absolute loads increased individually due to the subjects' improvements. MS training was also based on progression, which was related to the subjects' improvement in 1RM. In addition, periodization of MS-P training program, in which maximum strength training was followed by power training, included mesocycle level progressivity (Table 2). MS and P training programs included leg press, knee extension, bench press, and shoulder press exercises. Other exercises were trained similarly as in HYP program. During the P period subjects performed one maximum strength session after every three weeks in order to maintain their maximum strength levels.

TABLE 2 The progressiveness of the strength training programs

		Sets	Repetitions	Load	Rest			Sets	Repetitions	Load	Rest
	1-4wk	2-3	12-14	60% 1RM	1 min		11-13wk	2-3	12-14	60% 1RM	1 min
HYP I	5-7wk	2-3	10-12	70% 1RM	2 min	HYP II	14-16wk	2-3	10-12	70% 1RM	2 min
	8-10wk	3-4	8-10	80% 1RM	2 min		17-20wk	3-4	8-10	80% 1RM	2 min
	1-4wk	2-3	6-10	70-75% 1RM	3 min		11-13wk	3	4-10	30-70% 1RM	3 min
MS	5-7wk	3-4	4-10	70-85% 1RM	3 min	P	14-16wk	4	4-8	30-50% 1RM	3 min
	8-10wk	2-6	3-9	80-90% 1RM	3 min		17-20wk	5	6-8	30-50% 1RM	3 min
							Sessions to maintain max strength levels during the power period				
							At 11wk/1st	3	4-6	87,5% 1RM	3 min
							At 14wk/1st	3	3-5	90% 1RM	3 min
							At 17wk/1st	3	2-4	92,5% 1RM	3 min

Note: MS and P training programs included leg press, knee extension, bench press and shoulder press exercises and other exercises the same as with HYP program.

4.5 Data collection and analyses

4.5.1 Anthropometric and muscle cross-sectional area

Height and body mass. Subject's height and body mass were measured during the familiarization session in the beginning of the cross-sectional studies (in experiment 1 and 2) or morning after overnight fast (12 hours) before and after 10- and 20-week strength training during longitudinal studies (in experiment 3 and 4). Body mass and height were obtained by calibrated floor and wall-mounted measurement scales, respectively. The subjects were instructed to avoid exercise for 48 hours before all anthropometric measurements.

Muscle cross-sectional area. In experiments 3 and 4, cross-sectional area (CSA) of the vastus lateralis muscle was assessed using B-mode axial-plane ultrasound (SSD-α10 model, Aloka Co Ltd, Tokyo, Japan). Anatomical landmarks for CSA determination were the middle section between the joint space on the lateral side of knee and the greater trochanter. 50% of femur length was then marked subcutaneously with ink, which ensured that the measurements were valid and comparable throughout the whole intervention. A 10 MHz linear-array probe (60 mm width), with extended-field-of-view settings, was moved (slowly and continuously) manually across the sagittal plane from the lateral to medial diaphysis of the right thigh along a marked line on the skin, while avoiding any compression of the muscle tissue. All recorded ultrasound images were combined automatically to a panorama-view via in-built software. Three panoramic CSA-images were recorded and CSAs were determined by manually tracing along the borders of the vastus lateralis muscle images using Image-J software (version 1.37, National Institute of Health, USA). The mean of two closest CSA-images were averaged as the results for CSA measurement. One well-experienced person analyzed all the images for the same subjects and all the measurement time-points throughout the intervention were analyzed by the same person. The reliability and validity of this CSA determination method has been shown and reported to be good (Ahtiainen et al. 2010; Noorkoiv et al. 2010).

4.5.1.1 Isometric performance

Knee extension. The first three (1-3) experiments included isometric unilateral maximal voluntary knee extension contractions (MVC) with the same anthropometric settings; a knee joint angle at 107° and hip angle at 110° (180° is full extension). Subject position was ensured by a non-elastic belt at the hip and a pad across the knee to focus force/torque production correctly. In experiments 1, 3 and 4, isometric knee extension measurements were performed on a separate isometric dynamometer (Department of Biology of Physical Activity, University of Jyväskylä). During experiment 1, the use of a separate isometric dynamometer ensured comparable results between pneumatic and weight-stack devices, however, this separate isometric dynamometer was not the device that was used for training. In experiments 2, 3, and 4, the same weight-stack loading device (David 200; David Health Solution Ltd., Helsinki, Finland) as in cross-sectional experiments (1 and 2) was modified with a locking system and force sensors to allow assessment of MVC tests in an isometric condition.

Leg extension. Maximal bilateral isometric strength of leg extensor muscles was measured on a custom-built horizontal leg press dynamometer (Department of Biology of Physical Activity, University of Jyväskylä) during experiment 3 and 4. Tests were performed in a seated position with knee joint angle at 107° and hip angle at 110°, respectively. The subjects were instructed to use their maximum effort and push "as fast and hard as possible". Subjects maintained their maximum force levels for approximately 3 seconds.

Isometric training monitoring. Experiment 3 and 4 included monitoring tests in the gym. These monitoring tests were performed at the beginning of every 7th training session, but always after the warm-up trials. The used test device was the same isometric horizontal leg press dynamometer as in the laboratory measurements; also the settings and instructions were the same. In addition, leg extension dynamometer tests were performed immediately after the leg press exercise (the first exercise in the gym sessions) to indicate acute responses to the current strength training protocol in force production including also fingertip blood lactate tests during experiment 4.

4.5.1.2 Dynamic performance

Knee extension. Comparisons between different resistance modes in experiments 1 and 2 were performed on bilateral knee extension devices in a seated position. In experiment 1, pneumatic (Hur 3350; Hur Ltd. Kokkola, Finland) and weight-stack (David 200; David Health Solution Ltd., Helsinki, Finland) resisted devices were used. The same weight-stack device was modified by an additional elastic resistance in experiment 2. Although the inertial characteristics of the resistance differ between the devices and resistance modifications, they all provide variable resistance; the pneumatic system included lever arms and the weight-stack system utilized a cam wheel in the mechanism. In the latter one, the additional elastic resistance also increased resistance during knee extension. The range of the knee extension was from 60 to 180° knee joint angle and the hip joint angle was fixed, secured by a belt, to 110° throughout the movement. In addition, a separate knee goniometer was attached to the leg around the knee joint to synchronize torque and EMG signals and in order to compare joint angles between different loading devices in experiment 1.

In experiment 1, subjects performed randomized single explosive contractions of 20% 1RM, 40% 1RM, 60% 1RM, 80% 1RM with 2 minutes recovery between trials after the determination of 1RM in both resistance modes. Before 1RM determination, the subjects first performed a progressively increasing warm-up protocol (1 x 10 x 70% estimated 1RM, 1 x 7 x 75% estimated 1RM, 1 x 5 x 80% estimated 1RM, 1 x 1 x 90% estimated 1RM). Thereafter, maximal strength was determined by three to four separate repetitions using 2.5 kg increments until the subject could no longer lift to full knee extension. Verbal encouragement was given to subjects during maximal performances. In addition, experiment 2 presents e.g. data from separate explosive repetitions during unfatigued and fatigued conditions, but only at 40% 1RM load. Each of these single and separate repetitions were analyzed for six 20° windows, from 60° to full extension (180°) knee joint angle. Resistance mode order was also randomized and the 1RM determination protocol was the same as in experiment 1, but 1RM was determined at least 7 days earlier using the weight-stack device without additional elastic resistance.

These experiments included measurements to determine acute neuromuscular changes and fatigue, during and after different loadings. Experiment 2 compares dynamic performances between unfatigued and fatigued conditions with kinetic, kinematic and electromyographic data, using also 20° windows, from 60° to full extension (180°) knee joint angle in the analysis.

Leg extension. The range of the leg extension was from 60 to 180° knee joint angle and 110° hip joint angle, which was secured by a belt. Maximal strength (1RM) was determined using the same protocol and criteria as in knee extension performances during experiments 1 and 2. Single explosive repetitions were performed using current relative 50% 1RM load but also absolute 50% 1RM load based on subject’s strength level before training. The subjects were encouraged to extend their legs “as fast and hard as possible”.

4.5.1.3 Force and angle signal sampling and analysis

Calibration of all force and angle sensors were accomplished before the beginning of each test period. All force, torque, (concentric and isometric) and angle signals were sampled at 2000 Hz and signals were low pass filtered (torque 20 Hz, and angle 75 Hz). Mean angular velocity, accelerations and power (torque × angular velocity) values during concentric repetitions were analyzed in 20° jointangle segments. Mean power was calculated as the mean angular velocity multiplied by the mean torque for each sector separately. Both before and after loading as well as pre-, mid- and post-training, the plateau of isometric MVC was used to determine mean maximal torque over 250ms (in experiment 1) and 1000ms (in experiments 2 and 3) time windows. The rates of torque or force development during the initial 100ms and during the greatest 10ms slope were analyzed from the fastest MVC trials during that measurement session, which were measured separately from the other MVCs with electrical stimulation. In the analysis, the definition of the start of contraction was based on the first sharp increase in force signal.

4.5.1.4 Electromyography measurements and analysis

Electromyography. In all experiments (1-4) surface electromyography (EMG) was used. Surface EMG electrodes were positioned above vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF) and biceps femoris (BF) muscles of the right leg using bipolar Ag/AgCl electrodes (5 mm diameter, 20 mm inter-electrode distance, common mode rejection ratio > 100 dB, input impedance > 100 MΩ, and baseline noise < 1μV rms; (Beckman miniature skin electrodes 650437, Ill., USA) after shaving and abrasion of the skin, according to SENIAM guidelines (Hermans et al. 1999). EMG signals were sampled at a frequency of 2000 Hz, and pre-amplified at a gain of 500 (sampling bandwidth 10–500 Hz). Signals were passed real time through an analog-to-digital (A/D) board converter (Power 1401) to a computer using Signal 2.16 software (Cambridge Electronic Design, Cambridge, United Kingdom). In the data analysis, EMG signals were bandpass filtered (20–350 Hz) and transformed to root mean square (rms) form of EMG amplitude before being normalized to the corresponding EMGrms value measured during isometric MVC during each measurement session. Electromyographic activities of the VL and VM muscles were combined and averaged (e.g. (VL+VM) / 2). Rectus femoris muscle activity was not measured because of the muscle stimulation electrodes during experiments 2, 3 and 4.

EMG signals from bilateral isometric knee and leg extensions were analyzed by a customized script (Signal 2.16, CED, UK). Maximal EMG activity was analyzed from the plateau phase of isometric MVC over a 1000ms time window between 500 and 1500ms from the beginning of the MVC contraction. In experiment 1, this time window was 250 ms. EMG activity during rapid torque production was analyzed from the initial 100 milliseconds of isometric MVC (EMG100 milliseconds). In the original paper II, the averaged median frequency of the VL and the VM muscles were determined from isometric EMG over the force plateau's most stable 1000ms time window by fast fourier transformation (Hanning windowing, 2048 data points) during knee extension MVC before and after the loading. In addition, bilateral dynamic concentric knee and leg extension EMG signals were collected and analyzed for each of the six 20° knee joint angles.

4.5.1.5 Electrical stimulation measurements and analysis

In all experiments (1-4) a constant current stimulator (Digitimer Stimulator Model DS7AH; Digitimer Ltd., Hertfordshire, United Kingdom) was used to transcutaneously stimulate either the quadriceps muscle (1, 3 and 4) or the femoral nerve (2) with supra-maximal electrical monophasic rectangular pulses (1ms, 400 V). These electrical stimulations were performed pre- and post-loadings (experiments 1 and 2) and pre-, mid-, and post-training (3 and 4). During electrical stimulations, force signals were collected using a separate isometric knee extension device (experiment 1) or the knee extension weight-stack device in the locked isometric position (experiments 2, 3, and 4).

Muscle stimulations. Two pairs of carbon film muscle stimulation electrodes (V-Trodes; Mettler Electronics Corp., Anaheim, CA, USA; diameter 70 mm) were placed on to the mid and distal portion of the quadriceps muscle group (right leg). Stimulation electrode pairs were galvanically separated, and the skin under the electrodes was shaved and cleaned. Unilateral isometric knee extension torque responses from the stimulation during resting condition were determined at the 107° knee joint angle on the measurement device. The current was increased progressively in 20 mA steps between stimulations when the torque response was higher than that of the previous stimulation. When the maximal torque response was reached, 50% of the stimulation current was added. According to Merton's (1954) interpolated twitch technique, this supra-maximal stimulus (150%) was used for all subsequent stimulations. Monitored EMG from biceps femoris (BF) muscle showed that the used methods did not stimulate antagonist muscles. Resting stimulations were performed 2 times with 1 minute between the twitches. Resting twitch torque, rate of twitch torque development (RTTD), and half-relaxation time (1/2RT) were analyzed from each twitch. The used superimposed twitch (SIT) protocol included RTs before and after MVC, and the first twitch was delivered during the plateau phase of MVC. The subjects were instructed to increase their torque progressively towards the maximum, and they were able to reach MVC within 5 seconds. Voluntary activation level was calculated according to the formula by Bellemare and Bigland-Ritchie (1984):

$$\text{Activation level (\%)} = [1 - (Pts / Pt)] \times 100,$$

where Pts is the difference between the voluntary torque and twitch torque from the SIT, and Pt is the RT torque after MVC.

Peripheral nerve stimulations. In experiment 2, the stimulator was used to excite the femoral nerve beneath the inguinal ligament. The cathode (1 cm diameter) was attached into the femoral triangle at the placement that gave the strongest response to a weak stimulation current. This location was marked on the skin for replacement. The anode was attached on the greater trochanter. Monophasic rectangular pulse wave was delivered to evoke maximal compound mass action potentials (M-wave) in vastus lateralis (VL) muscle. M-wave amplitude was followed after every 10 mA current stages until there were plateaus in the M-wave amplitude (again 50% of the stimulation current was added for the measurements). Latency time, peak-to-peak amplitude, and duration of M-wave were measured in a fully upright standing position with the subjects' bodyweight balanced equally between both legs, feet hip width apart.

4.5.2 Blood sampling and analyses

Fingertip blood samples were taken to determine capillary blood lactate levels before the warm-up and immediately after the loadings during experiments 1, 2 and 4. Blood samples were collected with 20 µL capillary tubes and mixed with 1 mL hemolyzing solution. Automatic blood lactate analysis was performed according to the manufacturer's (EKF Diagnostic, Biosen, Germany) instructions after testing.

During experiment 3, basal venous blood samples were collected using sterile techniques with the blood transferred into serum tubes (Venosafe, Terumo, Belgium) from an antecubital vein before and after 10 and 20 weeks of training. These resting, basal serum blood samples were obtained at the same time (±1 hour) of the morning between 7:00-9:00am on every measurement point, after 12 hours fasting and 48 hours abstinence from exercise. The collected blood samples were centrifuged for 10 min at 3500 rpm (Megafuge 1.0R, Heraeus, Germany), after being held for 15 min at room temperature. Once red blood cells had been separated from the serum, the serum was pipetted and stored (-80 °C) in tubes for future analysis.

Total testosterone (TT), cortisol (C) and sex hormone-binding globulin (SHBG) were analyzed from serum samples (Analytical sensitivity; TT = 0.5 nmol/L, C = 5.5 nmol/L, SHBG = 0.2 nmol/L) using the Immulite 1000 and hormone-specific immunoassay kits (Immulite, Siemens, Illinois, USA) by immunometric chemiluminescene techniques. Intra- and Inter-assay reliability (CV%) of total testosterone and cortisol were within acceptable limits (TT = 5.7% and 8.3%, C = 4.6% and 6.1%, SHBG = 7.6% and 7.5%). All samples for each participant were analyzed in the same assay for each hormone. The TT/SHBG, FAI (free androgen index = 100 × (TT/SHBG)) and T/C –ratios were calculated, as also free testosterone (FT) via albumin concentration, after these analyses.

4.6 Statistical analyses

Standard statistical analyses were used for descriptive variables; means, standard deviations (SD), standard errors (SE) and 95% CI by SPSS™ software (SPSS Inc, USA). Normal distributions were checked based on the criteria of Shapiro-Wilk Tests and acceptable levels of skewness and kurtosis. Homogeneity of variance was tested by Levene's Test. All dependent variables were assessed by using a two-way analysis of variance (ANOVA) with repeated measures. When a significant F-value was observed, Bonferroni post hoc procedures were performed to locate the pair-wise differences. The relative changes were analyzed with a paired two-tailed Student's t-test. The alpha level $p < 0.05$ criterion was used for statistical significance.

The reproducibility of the used parameters was examined by calculating the coefficient of variation (CV) and inter-session intra-class correlation coefficients (ICC), assessed from the unfatigued condition between different loading sessions (Table 3). These reliability values for the measurements used were at acceptable levels and these were partially reported in the original paper 2.

TABLE 3 The coefficient of variation and inter-session intra-class correlation coefficients of selected variables.

Variable	ICC	CV%
Isometric torque	0.981	3.4%
EMGrms	0.918	7.2%
EMG median frequency	0.957	6.8%
Maximum twitch torque	0.994	1.3%
Maximum RTTD	0.997	3.2%
Calculated voluntary activation	0.732	1.9%
M-wave amplitude	0.92	7.4%
M-wave duration	0.77	11.0%

5 RESULTS

5.1 Effects of the different resistances during single-repetitions (I-II)

5.1.1 Weight-stack versus pneumatic resistance

The torque–angle relationship between weight-stack and pneumatic resistance was significantly different ($p < 0.001$-0.05) at all knee joint extension angles from 60° to 160° during 1RM loads. The greatest concentric torques (1085 ± 157 Nm (weight-stack) and 825 ± 188 N (pneumatic) were produced at 100–120° knee joint extension angles on the weight-stack and 120–140° on the pneumatic device. During repetitions at all submaximal loads (20-80% 1RM), the weight-stack offered the greater ($p < 0.001$-0.05) resistance from 60–100°, whereas the pneumatic device offered it at the end of movement (160–180° knee joint angles) (Fig. 23).

The duration of the concentric phase of contraction increased and mean angular velocities reduced in both resistance modes when the resistance level was increased. The concentric contraction times were significantly ($p < 0.001$) shorter with pneumatic resistance, when 20%, 40% or 60% of 1RM resistance level were compared to the same resistance level on the weight-stack device (Fig. 24a). Angular velocities increased significantly ($p < 0.001$–0.05) until the knee joint angle of 140° from the flexed knee position (60°) on the weight-stack device with all loads. However, angular velocities did not change during this range of knee joint angles on the pneumatic device. At the beginning of the movement, at knee joint angles between 60–80°, accelerations were 4–10 times greater ($p < 0.001$) using pneumatic resistance than weight-stack resistance at all resistance levels.

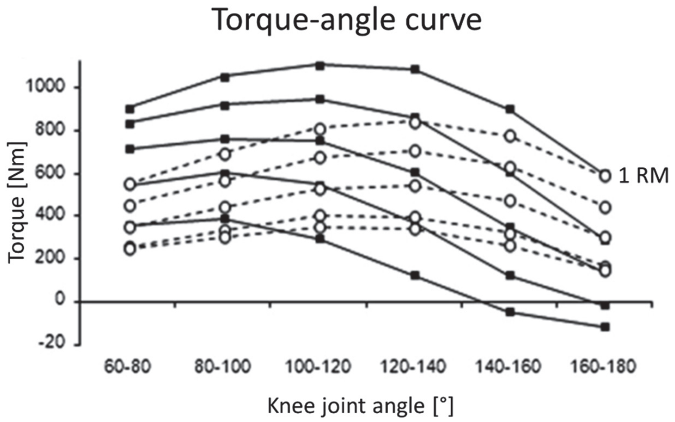

FIGURE 23. Torque-angle curve during single explosive (20%, 40%, 60%, 80% 1RM) and maximal (1RM) repetitions. Solid line is weight-stack and dashed line is pneumatic resistance.

Generated mean power was significantly higher ($p < 0.001–0.05$) during the repetitions of 20% and 40% 1RM with pneumatic resistance (1009 ± 232 W, 891 ± 362 W) in comparison to the weight-stack resistance (436 ± 229 W, 664 ± 289 W). Using the maximal resistance, the subjects reached higher ($p < 0.001$) mean power values with weight-stack (9 ± 3 W) than with pneumatic resistance (3 ± 2 W). Moreover, the total workload was greater on the weight-stack than pneumatic resistance, when using high or maximal load levels (80-100% 1RM) (Fig. 24b).

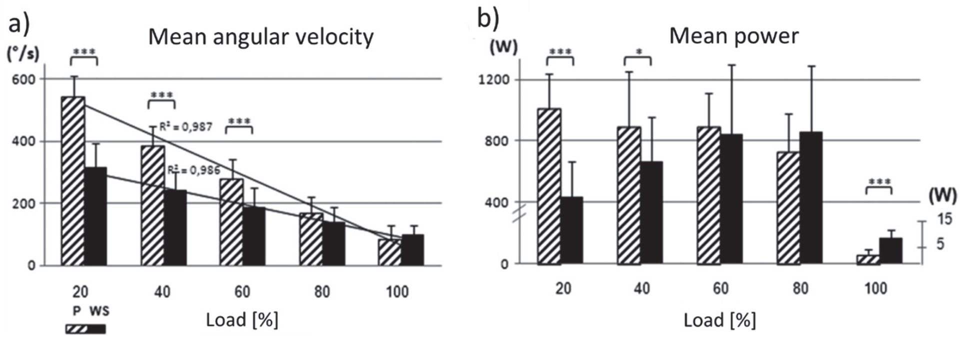

FIGURE 24. a) Mean angular velocity and b) mean power output during single explosive (20%, 40%, 60%, 80% 1RM) and maximal (1RM) repetitions between weight-stack (black bars) and pneumatic (striped bars) resistance. * p<0.05, *** p<0.001.

Muscular activity of the quadriceps muscles [(VL + VM + RF)/3] was initially (60–80°) higher ($p < 0.01$-0.05) during 20–60% 1RM resistance levels on the pneumatic than on the weight-stack resistance. Conversely, during the highest velocities, at the end phase of the movement at 20% and 40% 1RM resistance, muscle activity showed a decreasing trend on the pneumatic resisted devices. However, during the repetitions at the maximal or near maximal (80% 1RM) resistances muscle activities did not differ between these resistance modes.

5.1.2 Weight-stack with and without elastic resistance

Throughout the initial 20° (from 60 to 80°) knee joint angles, the torque-angle relationship between the resistance modes was identical, but thereafter resistance increased due to the additional elastic band, significantly at all knee joint angles from 80 to 180° compared to weight-stack resistance only. Adding the elastic band increased average resistance by 57 ± 26% ($p < 0.001$) and average power by 59 ± 26% ($p < 0.001$), however, average velocity reduced by 7 ± 5% ($p < 0.001$) compared to pure weight-stack resistance (Fig. 25).

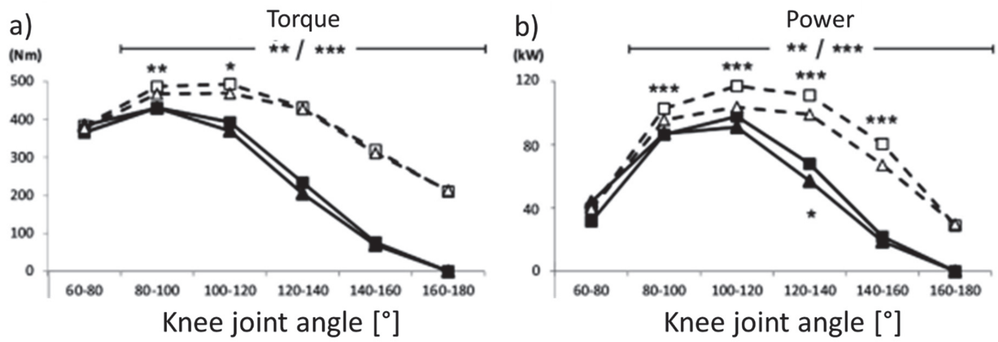

FIGURE 25. Weight-stack and weight-stack with elastic resistance a) torques and b) power output at 40% 1RM load before (□) and after (Δ) loadings. Solid line is weight-stack and dashed line is weight-stack with elastic resistance. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

According to these differences, the generated power was significantly greater at all knee joint angles from 80 to 180° with combined weight-stack and elastic band resistance, even though the angular velocities were significantly higher on pure weight-stack resistance after 100° knee extension angle.

Muscle activity reached peak values (206 ± 74% and 165 ± 72%; from pre-loading isometric EMG) significantly earlier and at smaller knee join angles on weight-stack without (343 ± 81 ms, 80–100°) than with additional elastic band resistance (474 ± 44 ms, 120–140°) (Fig. 26). Significant decrements were observed in the EMG activity of the quadriceps muscles during 80–120° knee angles on weight-stack with elastic band compared with that of weight-stack only resistance.

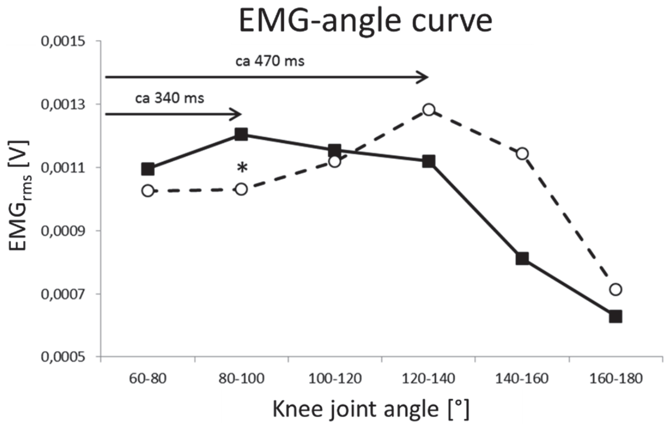

FIGURE 26. Time to reach peak EMG activities during explosive contractions against weight-stack and weight-stack with additional elastic band. Solid line is weight-stack and dashed line is weight-stack with elastic resistance. * $p < 0.05$.

5.2 Acute neuromuscular responses during loadings with different resistances

5.2.1 Maximum strength loading (weight-stack, pneumatic resistance)

After the maximum strength loadings isometric torque during MVC decreased significantly (pneumatic -18 ± 10% and weight-stack 22 ± 13%; $p < 0.05$–0.001). The maximum strength loading decreased both the maximal rate of force production (RFD) (pneumatic -24 ± 20% and weight-stack -26 ± 18%; $p < 0.001$–0.01) and the initial force production (0-100ms) significantly (pneumatic -22 ± 13% and weight-stack -21 ± 14%; $p < 0.001$–0.01). Resting twitch torque (−17 ± 20%, $p < 0.01$) and activation level (−13 ± 10%, $p < 0.05$) decreased significantly only on the weight-stack resistance after the maximum strength loading, however, no significant differences were observed between the resistance modes. In addition, maximal muscle activity decreased significantly ($p < 0.05$) after the maximal strength (−19 ± 14%) loadings on the weight-stack resistance, but not on the pneumatic. Blood lactate concentrations were not changed due to maximum strength loadings.

5.2.2 Power strength loading (weight-stack, pneumatic resistance)

The power loading with pneumatic resistance decreased MVC ($p < 0.01$) and the differences between pneumatic (-13 ± 9%) and weight-stack (-5 ± 12%) were statistically significant ($p < 0.05$). The RFD values were decreased significantly (pneumatic -19 ± 13% and weight-stack -16 ± 21%; $p < 0.01$) after both resistances. The reduction in the initial torque production during the first initial 100 ms took place without significant decrease in maximal torque only during the power loading on the weight-stack device (pneumatic -14 ± 12% and weight-stack -22 ± 14%; $p < 0.01$).

Power loadings induced significant ($p < 0.05$–0.01) decreases in the resting twitch torque during both weight-stack (−11 ± 15%) and pneumatic (−11 ± 10%) resistances. However, the activation level decreased (−8 ± 9%) significantly ($p < 0.05$) only after the power loadings with weight-stack resistance. In line with the activation level, maximal muscle activity decreased (−11 ± 19%) significantly ($p < 0.05$) after loadings with weight-stack resistance, but not with pneumatic. The power loadings did not change blood lactate concentration.

5.2.3 Power strength loading (weight-stack, weight-stack with elastic resistance)

The power strength loading with weight-stack resistance parallel with additional elastic resistance decreased torque production throughout the 80–120° knee joint angles of varying magnitudes (from -4 ± 2% at 120°, $p < 0.001$, to -3 ± 3% at 80°, $p < 0.05$, knee joint angles). Torque did not decrease significantly on weight-stack resistance alone. On the other hand, angular velocity decreased significantly during loading on both resistances; between 120 and 160° knee joint angles with weight-stack resistance and between 80–160° knee joint angles with weight-stack and elastic resistance. As a consequence, mean power decreased -11 ± 10% ($p < 0.05$) between 120 and 140° knee joint angles with weight-stack resistance whereas a reduction in power production was within a range from -8 ± 3% to -17 ± 6% ($p < 0.01$–0.001) between 80 and 160° knee joint angles during loadings on weight-stack with elastic resistance.

At the knee angles that produced peak concentric power (i.e., 100–120°), loading-induced reductions were greater ($p < 0.05$) after weight-stack with elastic resistance (-11.6 ± 8 kW) compared with weight-stack alone (-4 ± 10 kW). Root mean square of electromyographic activity of the dynamic contractions did not change significantly during loadings on both resistance modes.

Maximal isometric force decreased after loading by -6 ± 4% ($p < 0.01$) on the weight-stack and by ± 9% ($p < 0.05$) on the weight-stack with elastic resistance; however, maximal EMG activities during MVC did not change significantly after either resistances. The reductions in the initial force production (0-100ms) were -27 ± 26% ($p < 0.05$) and -16 ± 10% ($p < 0.01$) on the weight-stack and on the weight-stack with elastic resistances, respectively (Fig. 27a), but the reduction of EMGrms was significant only on weight-stack (-31 ± 22% p < 0.01). The RFD decreased similarly and significantly after both resistance modes (weight-stack -26 ± 17% and weight-stack with elastic resistance -28 ± 16% p < 0.001) (Fig. 27b). Moreover, loadings did not lead to significant changes in median frequencies in post-loading EMG activities.

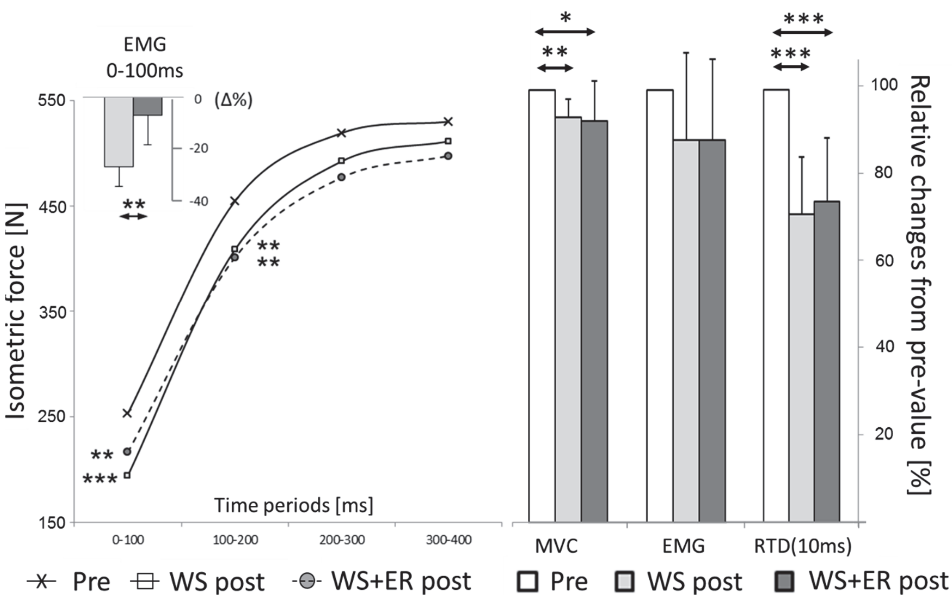

FIGURE 27. a) Isometric force-time curves before and after power loadings and the relative changes in initial EMG, and b) MVC, maximal EMG and RFD due to loadings. * p < 0.05, ** p < 0.01, *** p < 0.001.

The voluntary activation level declined significantly (-5 ± 7%, p < 0.05) only after the weight-stack with elastic resistance loading. Furthermore, changes in voluntary activation level were significantly different (p < 0.05) between the different resistance modes after loading. Resting twitch and RTTD were significantly enhanced and ½RT decreased after loading on both resistance modes. In addition, RT and RTTD were significantly higher after loading on the weight-stack with the elastic resistance mode than after the weight-stack resistance mode.

No statistical differences in maximal M wave parameters were observed; e.g. latency times, peak-to-peak amplitudes, or durations between pre and post-loading measurements or resistance modes. However, the averaged M-wave amplitude and activation level changed in parallel (Fig. 28), although individual variations were remarkable in both variables the changes due to weight-stack resistance were correlated after 30 minutes of recovery (r = 0.66, $p = 0.015$). Blood lactate concentrations increased from 1.8 ± 0.6 to 3.4 ± 1.3 mmol $\cdot L^{-1}$ and from 1.5 ± 0.3 to 4.3 ± 0.7 mmol $\cdot L^{-1}$ ($p < 0.001$), on the weight-stack without and with the elastic resistance, respectively, with a statistical difference ($p < 0.01$) between the resistance modes.

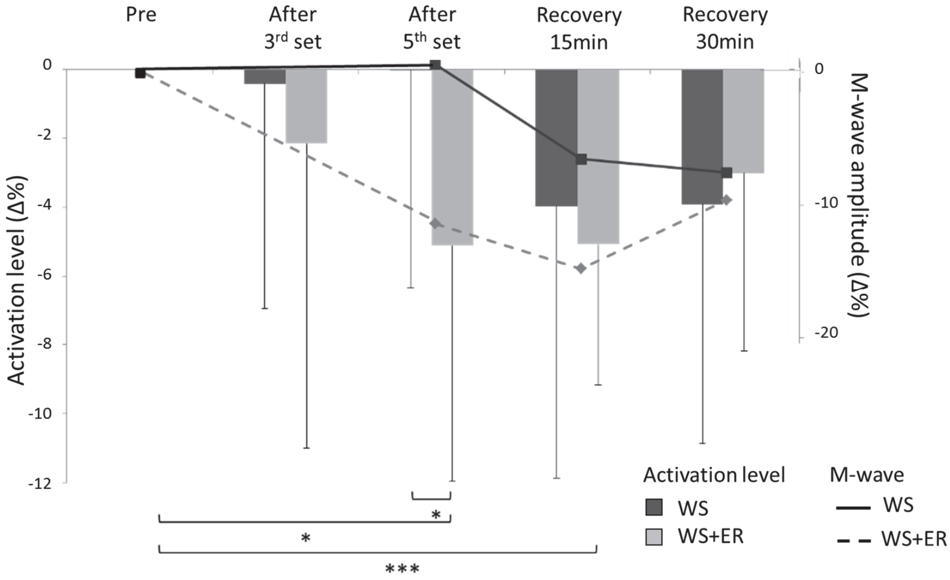

FIGURE 28. The changes in voluntary activation levels and M-wave amplitudes during power loading and recovery. * $p < 0.05$, *** $p < 0.001$.

5.2.4 Hypertrophic strength loading (weight-stack, pneumatic resistance)

Isometric torque during MVC decreased significantly ($p < 0.001$) after the hypertrophic loading on both resistances (pneumatic -37 ± 10% and weight-stack -38 ± 15%), without differences between the resistances. The RFD (pneumatic -41 ± 18% and weight-stack -29 ± 16%; $p < 0.001$) and the initial force production over the first 100ms decreased significantly ($p < 0.001$–0.01) after pneumatic (-40 ± 22%) and weight-stack (-29 ± 22%) resistances.

Electrical stimulation-induced resting twitch torque decreased significantly ($p < 0.001$) after the hypertrophic loadings with pneumatic (-63 ± 11%) and weight-stack (-71 ± 11%) resistances, but the changes were greater with weight-stack than with pneumatic resistance ($p < 0.05$). Concomitantly with the activation level (pneumatic +3 ± 14% and weight-stack +9 ± 15%), the hypertrophic loading in the weight-stack device induced significant ($p < 0.01$) increases (+26 ± 19%) in muscle activity during isometric MVC immediately after the loading, but changes were not significant on the pneumatic resistance (+3 ± 20%).

Blood lactate levels rose due to the hypertrophic loading on both resistances without any statistical differences between the resistance modes. Immediately after the loadings, blood lactate concentrations were 9.5 ± 1.2 mmol $\cdot L^{-1}$ with pneumatic resistance and 10.0 ± 1.0 mmol $\cdot L^{-1}$ with weight-stack resistance.

5.3 Short-term recovery after loading using different resistances

5.3.1 Maximum strength loading (weight-stack, pneumatic resistance)

Recovery between the sets with both weight-stack and pneumatic resistances restored peripheral capacities for each next set and three minutes rest between the sets were enough to maintain resting twitch force responses until to the 6th maximum strength loading set (Fig. 29). Thereafter, resting twitch force responses started to decrease set-by-set to the end of the maximum strength loading with weight-stack resistance compared to the maintained levels during the pneumatic loading. After 30 minutes of passive recovery from the end of the maximum strength loadings the resting twitch force responses were decreased due to the weight-stack (-35 Δ%) and the pneumatic (-23 Δ%) resistances.

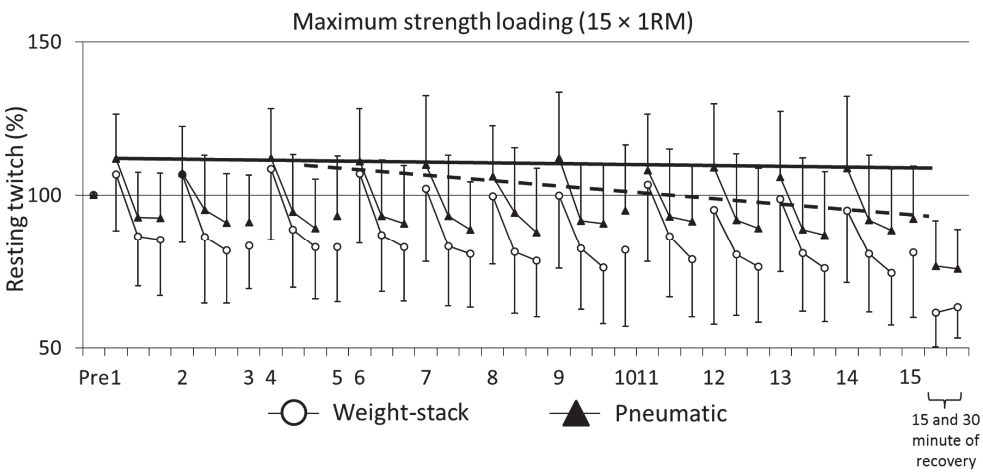

FIGURE 29. Resting twitch force responses between sets as well as 15 and 30-minute post-exercise of recovery during maximum strength loadings. Numbers in the x-axis means the start of the rest after set 1, set 2, etc. These twitch force responses were determined after every minute during 3-minute set rest, except after 3rd, 5th, and 10th sets only after 2-minute rest. The trendlines represent the changes in the resting twitch force responses due to loading; solid line is pneumatic, dashed line is weight-stack.

Three minute rest periods between sets were not enough to maintain voluntary activation level during sets of maximum strength and the activation level decreased (-13 ± 10%, p < 0.05) after loading with weight-stack, but recovered near to basal level during 30 minutes of recovery (Fig. 30). However, metabolic fatigue, defined as increased blood lactate levels, was not observed due to these loadings. After the pneumatic maximum strength loading, decreased RFD levels recovered slowly (~4 Δ%/30min). After weight-stack loading RFD levels recovered at faster rate (~15 Δ%/30min) (Table 4).

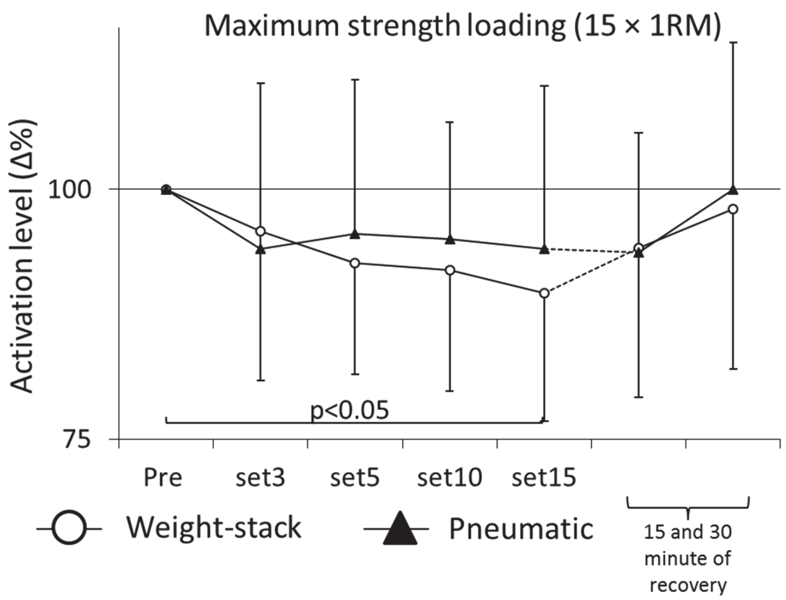

FIGURE 30. Activation levels before and after sets 3, 5, 10 and 15, as well as after 15 and 30-minute post-exercise recovery in maximum strength loadings.

5.3.2 Power strength loading (weight-stack, pneumatic, weight-stack with elastic resistance)

Three minutes of recovery between the sets of both weight-stack and pneumatic resistances restored peripheral capacities, assessed by passive twitch torque, until the last set (the fifth) of power loadings (Fig. 31, which includes pooled weight-stack data from experiment 1 and 2). After 30 minutes of passive recovery, power loadings induced parallel decrements as in maximum strength loading in resting twitch force responses for both weight-stack (-33 Δ%) and the pneumatic (-24 Δ%) resistances.

On the other hand, three minute set rest periods did not maintain voluntary activation level during power loadings with the weight-stack in experiment 1 (-8 ± 9%) (Fig. 32). However, 15 minutes was not enough to recover the activation levels after weight-stack with elastic resistance. Blood lactate levels did not change during loadings. After the weight-stack power loading, decreased RFD levels recovered slowly (~1 Δ%/30min) compared to maximum strength loading. However, RFD levels recovered after pneumatic power loading (~7 Δ%/30min) almost similarly with maximum strength loading (Tables 4 and 5).

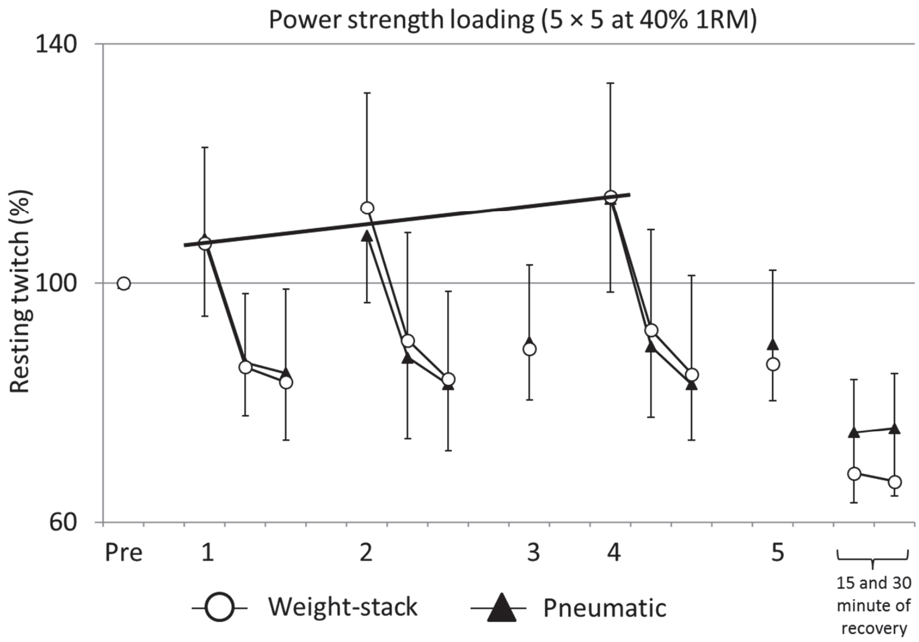

FIGURE 31. Resting twitch force responses during set as well as after 15 and 30-minutes of recovery during power strength loadings. Numbers in the x-axis means the start of the rest after set 1, set 2, etc. Twitch force responses were determined after every minute during rest, except after 3rd sets only after 2-minute rest. The trendline represents the changes in the resting twitch force responses due to loadings.

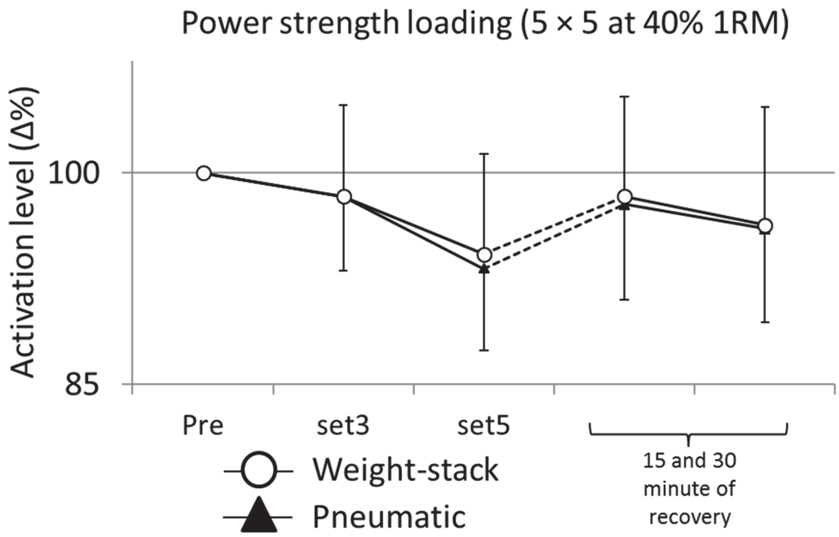

FIGURE 32. Activation levels before and after sets 3 and 5, as well as after 15 and 30 minutes of post-exercise recovery in power strength loadings.

5.3.3 Hypertrophic strength loading (weight-stack, pneumatic resistance)

Hypertrophic loading with weight-stack resistance induced a greater decrease (-36%) in resting twitch (peak) torque during the first set compared ($p < 0.05$) to pneumatic resistance (-25%) and the impairment of resting twitch levels were approximated 10% per set during both resistance modes until the end of the hypertrophic loading (Fig. 33).

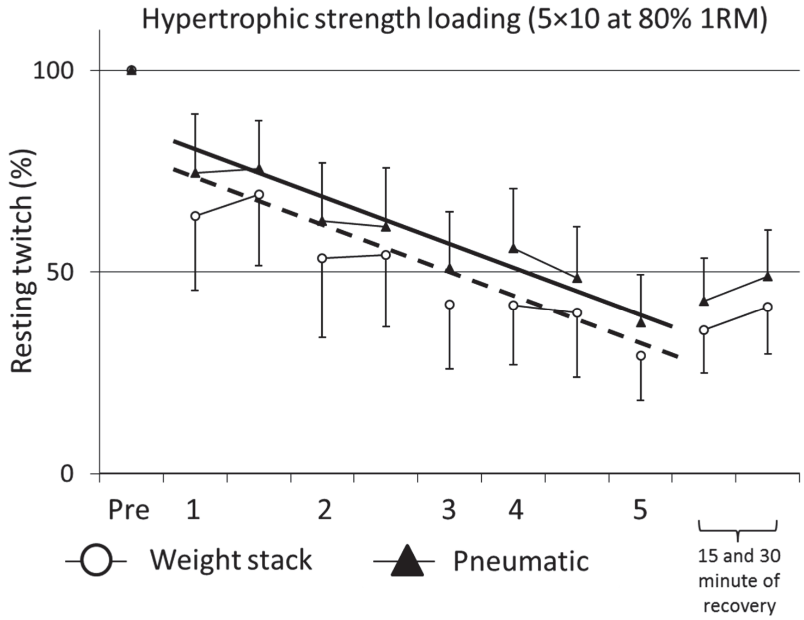

FIGURE 33. Resting twitch force responses during set as well as after 15 and 30 minutes of post-exercise recovery during hypertrophic loadings. Numbers in the x-axis means the start of the rest after set 1, set 2, etc. Twitch force responses were determined after every minute during rest, except after 3rd and 5th sets only after 2-minute rest. The trendlines represent the changes in the resting twitch force responses due to loading; solid line is pneumatic, dashed line is weight-stack.

Hypertrophic loadings induced increasing trends (n.s.) in voluntary activation levels with both pneumatic and weight-stack resistances (Fig. 34). In contrast to maximum strength and power loadings, the voluntary activation levels were slightly enhanced with both pneumatic and weight-stack resistances during hypertrophic loadings. However, activation levels decreased during post-loading recoveries from both resistance modes. In addition, after 30 minutes recovery, blood lactate levels were still slightly enhanced during both pneumatic (4.4 ± 1.4 mmol $\cdot L^{-1}$) and weight-stack (4.3 ± 1.2 mmol $\cdot L^{-1}$) resistance modes, and resting twitch responses were significantly reduced (WS -59 Δ% vs P -51 Δ%). Hypertrophic loading with pneumatic resistance caused greater decreases (−41 ± 18 Δ%) in RFD than weight-stack (−29 ± 16 Δ%), but the recovery rate during 30 minutes recovery period were similar (~15 Δ%/30min) between pneumatic (to −24 ± 22 Δ%) and weight-stack (to −14 ± 20 Δ%) resistances (Table 4).

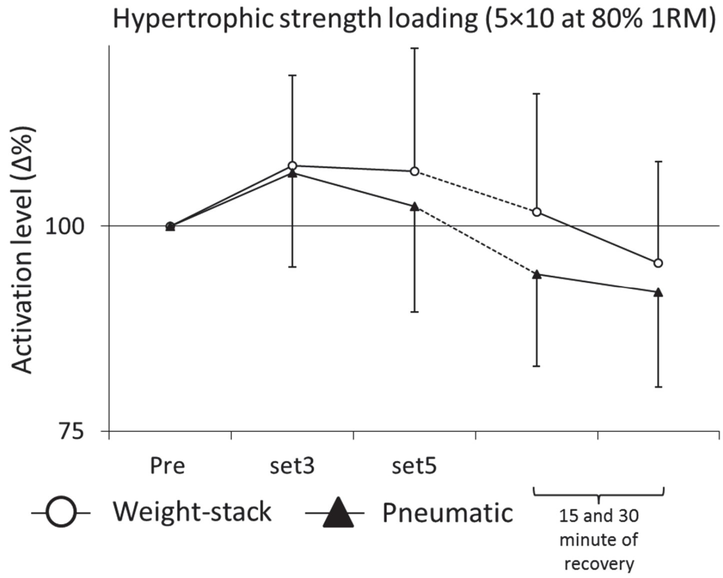

FIGURE 34. Activation levels before and after sets 3 and 5, as well as after 15 and 30-minute post-exercise of recovery in hypertrophic loading.

TABLE 4 Relative changes (Δ%) in initial force production, rate of force development (RFD), and rate of twitch force development (RTFD) after each loading at weight-stack (WS) and pneumatic (P) resistances.

		Force production [0-100ms]				RFD [10ms]				RTFD [10ms]			
		After loading		Recovery 30min		After loading		Recovery 30min		After loading		Recovery 30min	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Maximum strength	WS	-20,6 ±	14,2	-12,0 ±	10,9	-26,2 ±	17,8	-11,5 ±	16,4	-22,9 ±	22,7	-36,8 ±	10,0
15×1RM/3min	P	-22,3 ±	13,3	-20,3 ±	8,3	-24,3 ±	19,6	-20,3 ±	18,9	-4,6 ±	29,2	-24,2 ±	13,0
Power strength	WS	-21,6 ±	14,2	-13,9 ±	17,5	-16,4 ±	21,4	-16,0 ±	18,1	-19,9 ±	16,7	-33,2 ±	18,1
5×5×40%1RM/3min	P	-13,6 ±	11,6	-11,7 ±	6,2	-18,9 ±	13,3	-11,7 ±	16,4	-5,3 ±	29,9	-24,3 ±	11,4
Hypertrophic	WS	-29,4 ±	22,0	-13,4 ±	25,3	-28,7 ±	16,1	-14,0 ±	20,3	-64,8 ±	11,9	-58,6 ±	11,8
5×10×80%1RM/2min	P	-40,5 ±	22,1	-25,9 ±	19,8	-41,3 ±	17,8	-24,0 ±	22,1	-44,4 ±	26,7	-51,2 ±	11,6

TABLE 5 Relative changes (Δ%) in rate of force development (RFD), and rate of twitch force development (RTFD) after each power strength loading at weight-stack with (WS+RB) and without elastic resistance (WS).

		RFD [10ms]		RTFD [10ms]					
		After loading		After loading		Recovery 15min		Recovery 30min	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Power strength	WS	-26,0	17,0	10,0	8,6	-18,8	15,5	-18,9	6,1
5×5×40%1RM/3 min	WS+RB	-28,0	16,0	22,2	15,0	-16,2	12,6	-16,3	11,0

5.4 Monitoring of isometric parameters with long-term adaptations during strength training

Laboratory measurements. Bilateral concentric leg extension force (1RM) increased in both hypertrophic (0-10 wk) (8 ± 6%, $p < 0.001$) and maximum strength training periods (11 ± 6%, $p < 0.001$) after the first 10 weeks of training, but after the second hypertrophic (11-20 wk) period only a slight improvement (3 ± 4%) in 1RM took place that was not statistically significance. Similarly, the power training period maintained (1 ± 4%, n.s.) 1RM during the second 10-week period. EMGrms increased significantly (25 ± 30%, $p < 0.05$) during 1RM contraction only after 10 weeks of maximum strength training.

During explosive repetitions with the 50% 1RM load, initial velocity and, thus, power increased (11 ± 15%, $p < 0.05$) concomitantly with EMGrms (22 ± 26%, $p < 0.05$) only after power training. This was also observed in peak velocity and power (15 ± 18%, $p < 0.05$) and EMGrms (93 ± 105%, $p < 0.05$) at larger knee-joint angles (Fig. 35).

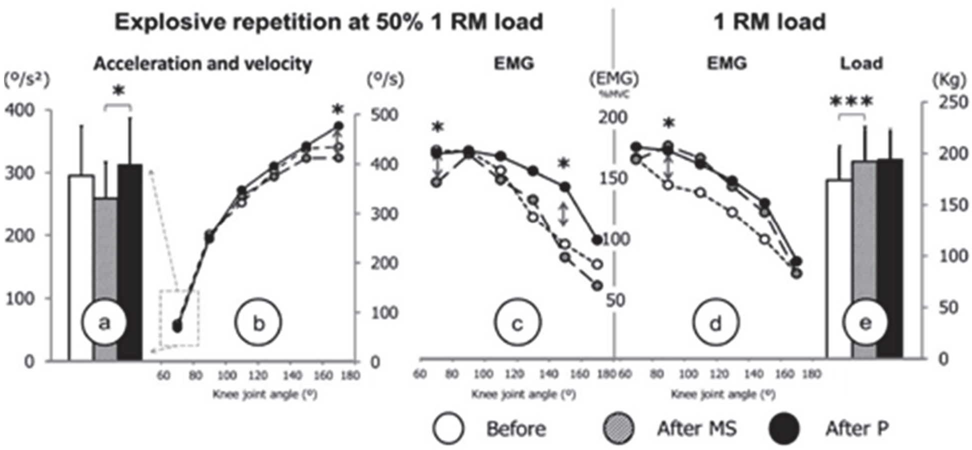

FIGURE 35. The changes after MS and P training in a) acceleration (60-80° knee joint angle) b) angle-velocity curve c) EMG during explosive repetitions at 50% 1 RM load d) EMG during 1 RM repetitions and e) 1 RM load. * $p < 0.05$, *** $p < 0.001$.

Activation level decreased significantly during the power training period (-5.4 ± 7%, $p < 0.05$), while the changes during the maximum strength, hypertrophic 0-10 week and 11-20 week periods or in the control groups were non-significant. Knee extension MVC increased during the maximum strength and hypertrophic 0-10 week (12.6 ± 11%, $p < 0.01$; 11 ± 12%, $p < 0.01$), but not during power or hypertrophic 11-20 week periods. The resting twitch peak force and the slope of the twitch force did not change significantly during the maximum strength, power or hypertrophic training periods at the group level (Table 6). The cross-sectional area of VL increased in both training modes during the first 10 weeks (hypertrophic 0-10 wk 16 ± 13% $p < 0.001$; maximum strength 7 ± 10%; $p < 0.01$), but the following 10-week hypertrophic training (hypertrophic 11-20 wk -1 ± 6%; n.s.) and power training (P -3 ± 5%; n.s.) periods only maintained CSA.

TABLE 6 Activation level, resting twitch force and the slope of resting twitch force values before, and after each training periods and control period. ‡ $p < 0.05$.

Subject group		Activation level [%]				Resting twitch force [N]			Resting twitch slope [N/s]		
		Pre	Mid		Post	Pre	Mid	Post	Pre	Mid	Post
MS-P	Mean	90.9	91.0	‡	85.6	50.2	51.1	45.5	903.5	904.3	810.3
	Sd	6.1	4.7		8.1	16.6	23.6	12.4	320.0	374.7	127.9
HYP	Mean	90.7	89.0		89.9	55.8	49.9	55.9	880.8	902.3	887.1
	Sd	3.1	7.7		7.1	15.2	11.6	13.0	227.2	197.8	169.3
Control	Mean	89.7			89.6	48.2		46.6	937.6		896.2
	Sd	7.3			6.3	7.4		20.1	145.3		243.9

Isometric knee extension RFD and resting twitch slope correlated negatively (r = -0.45, $p < 0.05$) after first 10 -week training period (combined hypertrophic 0-10 wk and maximum strength), and this trend (r = -0.618, $p = 0.076$) continued following power training, but not after hypertrophic 11-20 weeks. Relative changes in resting twitch slope and AL also correlated (r = 0.80, $p = 0.010$) after the power period. In addition, these changes in AL correlated almost significantly (r = 0.66, $p = 0.053$) with corresponding enhancements in dynamic peak power after the power training period.

The first 10-week training period (combined hypertrophic 0-10 wk and maximum strength) revealed a negative correlation (r = -0.49, $p = 0.02$) between the changes in isometric knee extension MVC and AL. This relationship turned positive and was stronger after power (r = 0.65, $p = 0.059$) than after hypertrophic 11-20 week training (r = 0.21, n.s.). In isometric knee extension, the increase in EMGrms over both the initial 100ms (37.7 ± 45%) and 500 ms (13 ± 48%) were related (r = 0.61, $p = 0.06$; r = 0.72, $p < 0.05$, respectively) to the increase in MF (10.4 ± 21%), again only after the power training period.

The increase in CSA over the first 10-week training correlated negatively with increase in EMGrms over initial 500 ms during isometric knee extensions (r = -0.63, $p < 0.05$) after hypertrophic 0-10 weeks period. The changes in CSA and AL negatively correlated (r = -0.84, $p < 0.001$) over the 20-week hypertrophic training period (0-20 weeks) (Fig. 36).

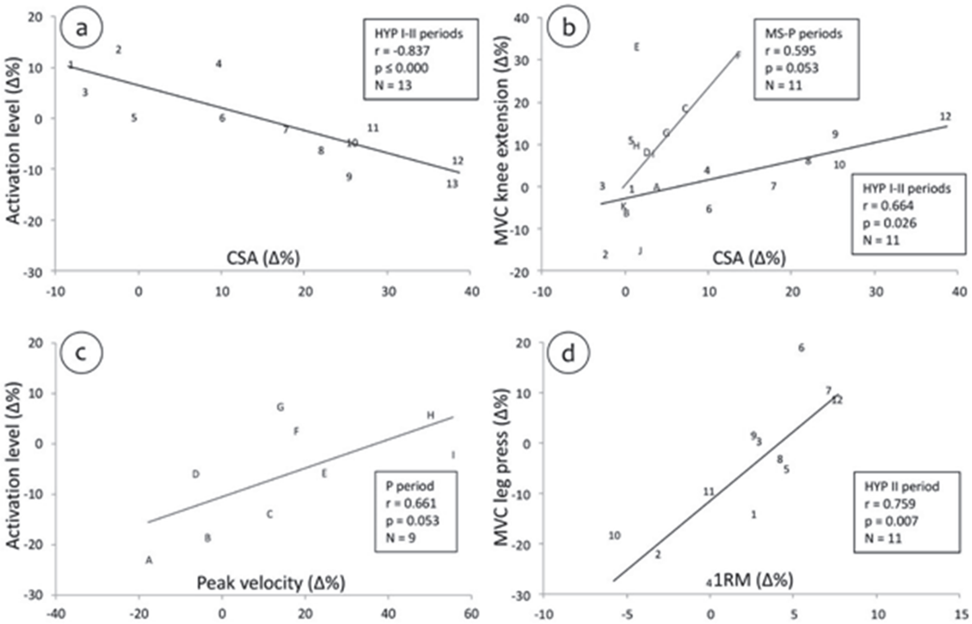

FIGURE 36. The correlations between relative changes of a) activation level and cross-sectional area (CSA) after 20 week hypertrophic training, b) isometric knee extension MVC and CSA after 20 week maximum strength and power training and hypertrophic training, c) activation level and leg press peak velocity at 50% 1RM after power training, d) isometric leg press MVC and dynamic leg press 1RM after 11-20 week hypertrophic training period.

Monitoring tests. Bilateral isometric leg extension RFD over the steepest 10ms of the force-time curve increased (44 ± 53%, $p < 0.05$ and 47 ± 73%, $p < 0.05$) similarly during the first 7 weeks in both hypertrophic 0-10 week and maximum strength training but thereafter, RFD continued to increase (65 ± 61%, $p < 0.01$ vs. baseline) only during maximum strength and power training. These changes in RFD followed the changes in leg extension MVC peak force during hypertrophic training (0-10 wk, r = 0.45; 11-20 wk, r = 0.59), but not during maximum strength or power training. MVC peak force increased during the first 10 weeks in both training groups (hypertrophic 0-10 wk 19 ± 20% $p < 0.01$; maximum strength 8 ± 12% $p < 0.05$). In addition, MVC correlated (r = 0.724, $p < 0.05$) with changes in the 1RM loads after hypertrophic 11-20 week, when 1RM was only maintained and MVC even decreased (-9 ± 4% $p < 0.001$) during power training (Fig. 37).

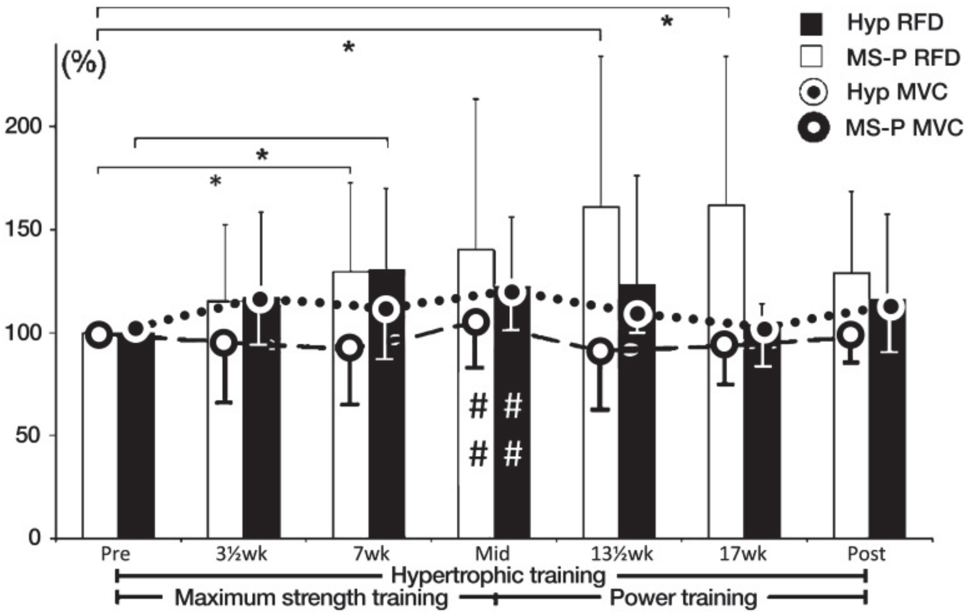

FIGURE 37. The changes in isometric leg press RFD and MVC peak force compared to before training. Note: RFD and MVC changed parallel during hypertrophic training, when the trends of these parameters differed clearly during maximum strength and power training periods ## $p < 0.01$.

Time to reach peak RFD did not differ between training groups in the beginning of the study, but at week 4 to 20 time to reach RFD differed significantly between hypertrophic and both maximum strength and power training periods (HYP 41 ± 18 ms, MS-P 32 ± 12 ms; $p < 0.05$-0.01, Fig. 38).

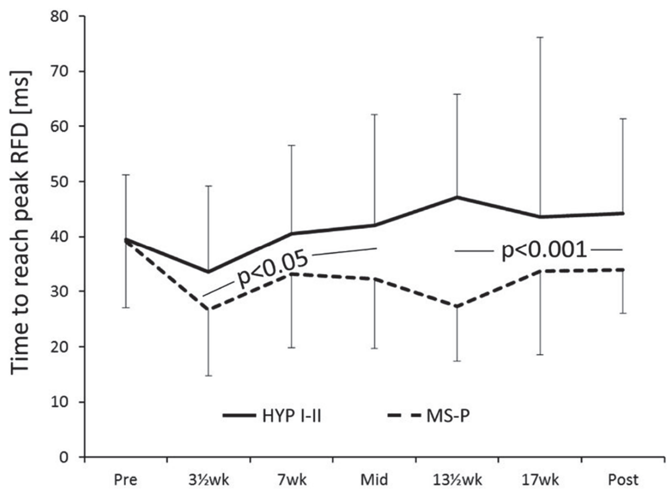

FIGURE 38. The time to reach peak RFD in isometric leg press during the time course of the two training modes.

The changes in monitored bilateral isometric leg press parameters were correlated to the changes in main training related dynamic performance (initial acceleration, peak velocity, and 1RM) and muscle size (CSA) parameters (Table 7).

TABLE 7 The correlations between relative changes of isometric leg extension monitoring parameters and main training specific parameters during 0 to 10 weeks (Pre-Mid), 11 to 20 weeks (Mid-Post) and 0 to 20 weeks (Pre-Post).

			Acceleration (0-20° knee joint angle)	Peak Velocity	1 RM	CSA
MVC	MS-P	Pre-Mid			r=-0.543 p=0.068	
		Mid-Post				
		Pre-Post			r=-0.611 p=0.046	
RFD	MS-P	Pre-Mid				r=0.571 p=0.041
		Mid-Post				
		Pre-Post				r=0.783 p=0.004
MVC	HYP	Pre-Mid				
		Mid-Post	r=0.584 p=0.059		r=0.759 p=0.007	
		Pre-Post			r=0.561 p=0.058	
TimeRFD	HYP	Pre-Mid				
		Mid-Post				
		Pre-Post	r=0.694 p=0.018			

5.5 Individual responses to maximum strength and followed by power training

The rate of force development over the steepest 10 ms part of the leg extension was used for the sub-group categorization based on the responses of the subjects to maximum strength (MS-responder) and power (P-responder) training or no response to either one (Non-responder). The averaged RFD from (4 wk to 10 wk) monitoring sessions during the maximum strength period improved (+100 ± 35%, $p < 0.001$) in MS responders, while P-responders increased only slightly (+11 ± 8%, $p < 0.001$) and Non-responders even decreased (-17 ± 11%, $p < 0.001$) their RFD during this period. The power training after maximum strength period improved the RFD of P-responders significantly (+53 ± 27%, $p < 0.001$) compared to their initial level, while MS-responders maintained their enhanced (+103 ± 46%, $p < 0.001$) RFD and Non-responders re-attained (+3 ± 9%; n.s) their initial level (Fig. 39a). The changes between the groups differed significantly ($p < 0.05$-0.001), with the exception of MS- and P-responders during the power training period (n.s.). After MVC normalization, the RFD of MS- and P-responders behaved similarly as without normalization, but the RFD of Non-responders followed P-responders trend ($R^2 = 0.66$) (Fig. 39b).

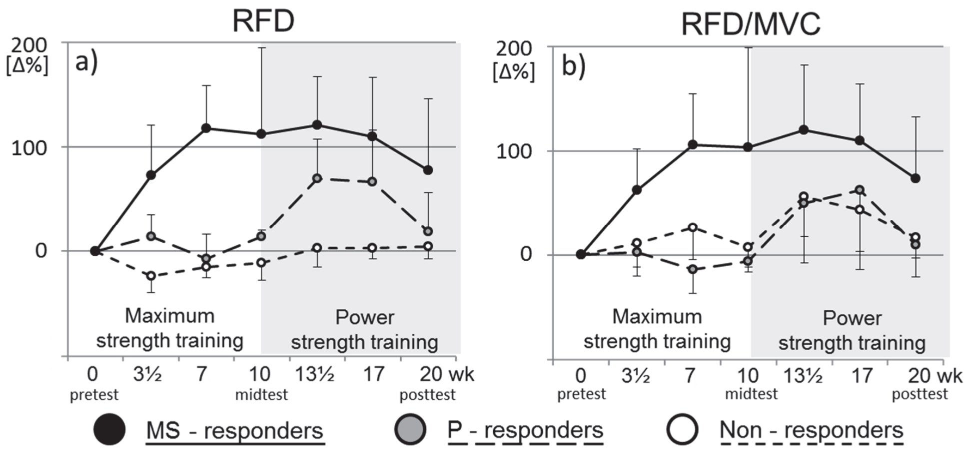

FIGURE 39. The relative changes in a) RFDs in subgroups and b) MVC normalized RFDs in subgroups during the maximum strength and power periods.

The initial level of leg press 1RM load and CSA of VL muscles were significantly lower (p<0.05) in the Non-responders (149 ± 21 kg, 23 ± 4 cm²) compared to the combined responder groups (MS 202 ± 20 kg, 29 ± 7 cm²; P 178 ± 23 kg, 29 ± 5 cm²). Relative changes of 1RM were similar between groups throughout both training periods, but CSA increased significantly only in the responders (MS +12 ± 9%, $p < 0.01$; P +10 ± 7%, $p = 0.07$) during the maximum strength period while Non-responders (+2 ± 3%, n.s.) maintained their CSA. In addition, only MS-responders enhanced their EMG (+113 ± 76%, $p < 0.01$) parallel with maintained 1RM (-1 ± 3%, n.s.) during the power period, although both MS- (-5 ± 4%, $p <$ 0.05) and P-responders (-5 ± 3%, $p = 0.07$) CSA decreased during the power period (Table 8).

TABLE 8 1RM leg press, CSA of vastus lateralis muscle and changes in EMG during 1RMs. * $p < 0.05$, ** $p < 0.01$ and # $p = 0.07$.

	Leg press 1RM (kg)			CSA of VL muscle (cm²)			EMG 1RM (Δ%) 60-180°		EMG 1RM (Δ%) 140-160°	
	Pre	10wk	20wk	Pre	10wk	20wk	0-10wk	10-20wk	0-10wk	10-20wk
MS	202±20 *	218±26	227±12	29±7 **	32±6 *	30±2	15±30	-1±19	-6±61	113±76 **
P	178±23 *	193±25	205±18	29±5 #	32±5 #	31±4	1±40	28±45	4±23	6±29
Non	149±21 *	168±21	173±15	23±4	24±9	23±4	15±22	1±28	27±68	29±13

*

During explosive leg press contractions at 50% 1RM load from the beginning of the study, MS-responders improved mean (+24%, $p = 0.076$) and peak (+35%, $p < 0.09$) power during the maximum strength period and these differed from the other groups significantly ($p < 0.001$ and $p = 0.07$). P-responders' initial EMG even decreased (-22 ± 14%, $p = 0.06$) during the maximum strength period, but then returned back to the initial level (+57 ± 10%, $p = 0.077$), parallel with EMG during the first half (+35 ± 18%, $p < 0.01$) of movement, during to the power period. MS- and Non-responders' EMGs were not changed systematically during either training period.

Electrical stimulation induced higher resting twitch force (+25% vs P; +47% vs Non), twitch force/time –ratio (+18% vs P; +45% vs Non) and twitch force/CSA –ratio (+30% vs P; +26% vs Non) in MS-responders compared to other groups at the beginning of the study. Before the power period, P-responders' AL was higher (+5%, $p < 0.05$) compared to Non-responders.

Basal blood sample analysis showed that hematological indices; hemoglobin (-2.8 ± 2.5% vs +0.4 ± 1.7%, $p = 0.08$) and hematocrit (-1.2 ± 1.6% vs +2.0 ± 2.6%, $p = 0.06$) behaved differently between P- and MS-responders during the maximum strength period, while no changes were observed for Non-responders. However, hemoglobin (+1.1 ± 2.2% vs -4.5 ± 1.6%, $p < 0.01$) and hematocrit (+1.4 ± 1.6% vs -3.6 ± 1.0%, $p < 0.01$) indices of P-responders were enhanced compared to Non-responders during the power period. IAt the beginning of the study, the SHBG level of Non-responders (+34%, $p < 0.05$) was elevated and partly therefore FAI –ratio (+34%, $p < 0.05$) was depressed compared to responders. Serum TT (MS -17 ± 12%, P -17 ± 22%; $p < 0.05$) and FT (MS -11 ± 10%, P -19 ± 24%; $p < 0.05$), as well as FAI (MS -12 ± 14%, P -21 ± 23%; $p < 0.05$) and T/C –ratios (MS -17 ± 25%, P -31 ± 20%; $p < 0.05$) were depressed in the responder groups, but not in Non-responders during the maximal strength period (Table 9).

Maximum strength leg press exercise in the gym in the present study (values present averages between weeks 3.5 and 7) induced greater decrements ($p = 0.068$) in the MVC of the MS-responders (-29 ± 9%) compared to the other groups (P -17 ± 6%, Non -18 ± 8%) during the maximum strength training period. In addition, at the same time averaged RFD of MS-responders decreased (-31 ± 6%), which differed almost significantly (p = 0.088) compared to the other groups (P -19 ± 13%, Non -23 ± 11%). However, P-responders blood lactate levels (+8.8 ± 1.7 mmol $\cdot L^{-1}$) were elevated significantly more than Non- (+5.0 ± 1.3 mmol $\cdot L^{-1}$, $p < 0.05$) or MS- (+5.5 ± 1.8 mmol $\cdot L^{-1}$, $p = 0.056$) responders (Fig. 40).

TABLE 9 Basal (cortisol, testosterone and sex hormone-binding globulin) hormonal levels and Free Androgen Index (FAI) and Testosterone/Cortisol ratios before and after the maximum strength (MS) and power strength (P) training periods in MS, P and Non -responders. * $p < 0.05$, ** $p < 0.01$.

		MS	P	Non
Cortisol [nmol/L]	Pre	515±163	461±148	622±148
	10wk	539±199	541±115	610±86
	20wk	490±157	573±84	562±88
Total Testosterone [nmol/L]	Pre	26±11	25±12	25±6
	10wk	21±6 *	19±6 *	22±6
	20wk	20±9	19±7	19±6
SHBG [nmol/L]	Pre	39±11	27±12 *	44±5
	10wk	42±13	29±13	45±6
	20wk	40±16	30±15	45±1
Free Testosterone [µmol/L]	Pre	0,43±0,20	0,44±0,21	0,39±0,10
	10wk	0,33±0,11 *	0,33±0,08 *	0,35±0,11
	20wk	0,31±0,16	0,32±0,11	0,29±0,11
T/C ratio	Pre	0,060±0,043	0,057±0,023	0,041±0,013
	10wk	0,044±0,022 *	0,037±0,013 *	0,036±0,006
	20wk	0,047±0,032	0,033±0,010	0,035±0,010
FAI	Pre	69±28	98±19 *	56±13
	10wk	51±14 *	78±34 *	50±16
	20wk	53±22	70±20	43±14

Power training leg press exercise in the gym (values represent averages between weeks 13.5 and 17) induced significantly ($p < 0.05$) greater decrements in the MVC of responders (MS -21 ± 5%, P -20 ± 8%) compared to Non-responders (-13 ± 3%). Any significant differences in RFD (MS -39 ± 15%, P -39 ± 17%, Non -30 ± 14%) or blood lactate levels (MS 5.4 ± 1.9 mmol ·L^{-1}, P 5.5 ± 1.3 mmol ·L^{-1}, Non 4.8 ± 1.5 mmol ·L^{-1}) were not observed between groups after leg press exercise during the power period (Fig. 40).

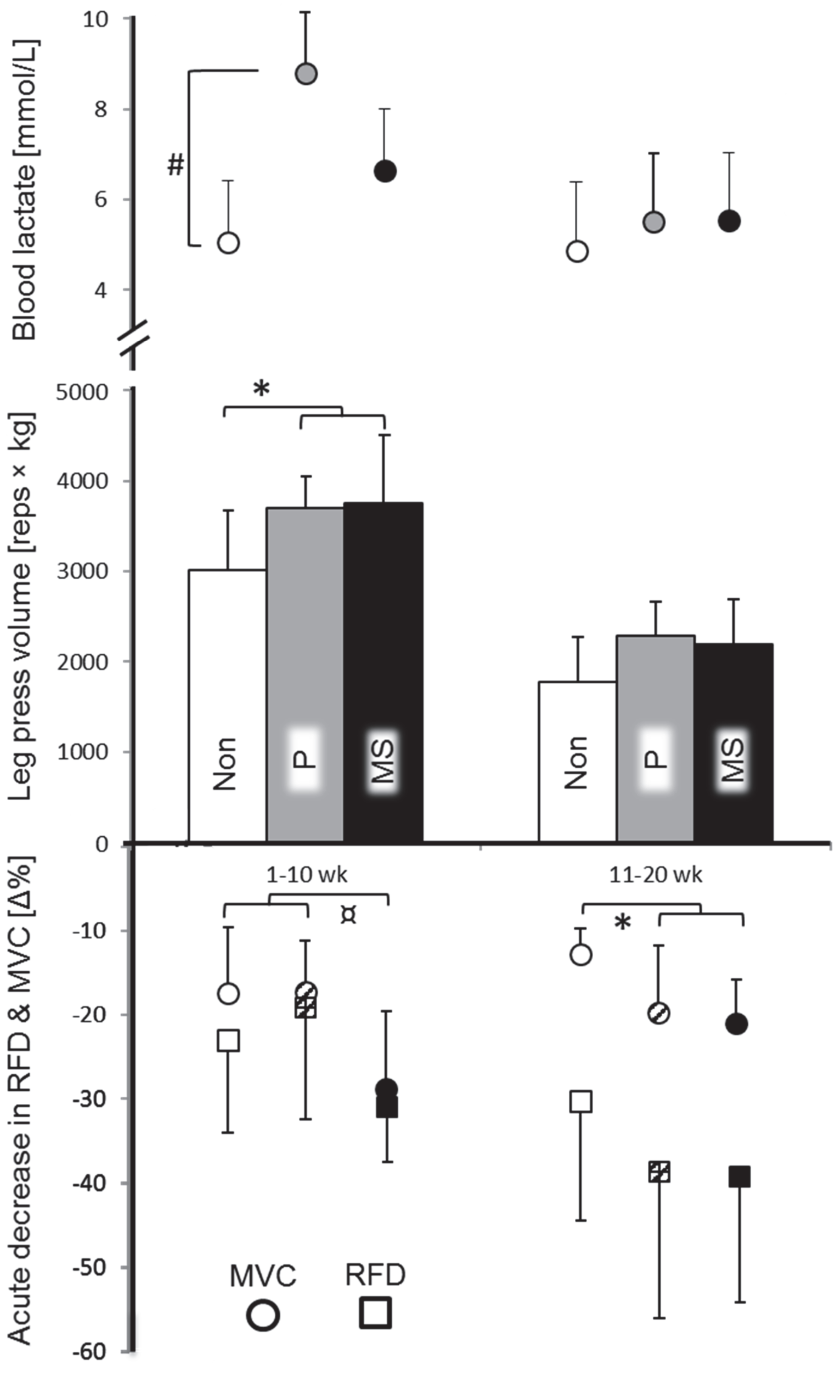

FIGURE 40. The average volumes of leg press exercises between sessions at weeks 3½ and 7 during the maximum strength period and at the 13½ and 17 during power period. The averaged acute decreases in RFD and MVC in the bottom and the averaged blood lactate levels in the top of the figure after leg press exercises. * $p < 0.05$, # $p = 0.056$, ¤ $p = 0.068$.

6 DISCUSSION

The main findings of the present study were as follows:

1) Resistance mode significantly affected the shape of the resistance-angle curve and thus muscle activities, torque productions, generated angular velocities, and power values. Therefore, repeated contractions induced differences in the fatigue profiles between the resistance modes.

2) The decreases in maximal isometric force production were greater after the hypertrophic and maximum strength loadings compared to the power loading in both pneumatic and weight-stack resistances. On the other hand, the reduction of maximal isometric force production was greater after power loading on the pneumatic than weight-stack resistance, but the reduction was similar with and without the additional elastic band in the weight-stack resistance.

3) The reduction in the rate of force production was specific for rapid actions following the power loadings on the weight-stack with or without the additional elastic band compared to pneumatic resistance. Both MVC and RFD decreased similarly during the maximum strength and hypertrophic type loadings in pneumatic and weight-stack resistances, although the reductions were greater after the hypertrophic loadings. However, pure weight-stack loading induced more neural-based fatigue, such as the reduction in muscle activity (EMG) during fast force production in isometric actions, compared to pneumatic loading and weight-stack loading with the additional elastic resistance. On the other hand, voluntary activation decreased more during MVC after weight-stack with the additional elastic resistance loading compared to pure weight-stack loading. Otherwise, voluntary activation behaved similarly between pure weight-stack and pneumatic resistance loading.

4) The time to reach peak RFD differed due to hypertrophic training and maximum strength and followed by power training. Hypertrophic training improved isometric peak RFD similarly to maximum strength training during the initial seven weeks, however neural enhancements via power strength training accompanied further improvements in peak RFD. MVC cannot identify the changes in hypertrophy alone, although the changes in MVC might be related to the changes in 1RM due to hypertrophic type long-term training.

5) Individual trainees could be categorized into maximal strength, power and non-responders based on their increase in RFD during periodized maximum strength and power training. These differences were mainly related to their initial pre-training CSA together with differences in anabolic and catabolic hormonal levels.

6.1 Effect of different resistances (I-II)

6.1.1 Explosive single-repetitions (I-II)

The resistance mode comparison showed the greater resistance in weight-stack compared to pneumatic resistance (between 60° and 160° knee joint angles) during 1RM load. The torque–angle relationship during weight-stack corresponded to maximal torque production capacities of the subject and, thus, followed the natural torque–angle curve more closely than with pneumatic resistance using the 1RM load. The effects of inertia and momentum on the torque-angle curve are lower when angular velocities are slower and the torque–angle relationship depends, then, mainly on the shape of the cam (Häkkinen et al. 1987). Conversely, when using lower loads and greater velocities of contraction, the greatest resistance and, thus, stress occurs at the initial part of the contraction on the weight-stack. The momentum of the weight-based resistance produced by the rapid acceleration phase overcomes the weight-stack resistance and, therefore there is a significant decrease in resistance at larger knee joint angles (e.g. 120–180°). Instead, the shape of the torque-joint angle curve remained the same when using different submaximal loads (e.g. 40% 1RM vs. 80% 1RM) in the pneumatic resistance. Mean angular velocities decreased linearly due to increased loads on both resistances, but the decline was steeper during pneumatic compared to weight-stack resistance. Instead, mean power behaved steadier between sub-maximal resistance levels on the pneumatic resistance, when the greatest and equal to the pneumatic mean power was reached only during 60 to 80% 1RM loads on the weight-stack resistance. Based on this, the use of pneumatic resistance for power and/or velocity training is preferred, especially, if the training goal is the development of continuous and prolonged power production with lower resistance (Frost et al. 2010).

The weight-stack with additional elastic band resistance can also offer greater concentric power after 80° knee joint angle compared to weight-stack only. However, the increased power is based on the expanded and increased resistance after narrow knee joint angles, which then decreases angular velocity after approx. 100° knee joint angle. High acceleration and, thus, higher angular velocities require enhanced muscular activities. Therefore, weight-stack only may induce more specific neural adaptation due to short and intensive contraction onset during power training compared to continuous and "longer" resisted contractions on the pneumatic or weight-stack with elastic band resistance. Recently, Frost et al. (2016) showed that pneumatic training might improve power production with lighter loads via higher accelerations and velocities compared to inertia-based resistances. Therefore, specific training with the potential advantages of different resistances (e.g. weight-stack, pneumatic and elastic) offers tools for different force-, velocity-, and power-related demands (Frost et al. 2016; Stevenson et al. 2010).

6.1.2 Neuromuscular responses after different loadings (I-II)

6.1.2.1 Maximum strength loading

Maximum strength loading caused isometric force decrements (-20–24 Δ%) throughout the entire force-time curve, but the amount of the reduction was only about half of that caused by hypertrophic loading after pneumatic and pure weight-stack resistance modes. Reduced volume load (0.375 × volume in hypertrophic loading) during maximum strength loading might explain this. In addition, the maximum strength protocol included longer recoveries (3 min) between sets, thus metabolic stress was not observed. The greater work done and mean power per every 15 maximal repetitions caused (larger) peripheral and central fatigue on pure weight-stack loading compared to pneumatic resistance loading. The decreased voluntary activation level, as well as decreased maximal EMGrms, is in-line with the studies of Häkkinen et al. (1988a) and Linnamo et al. (1998). Bigland-Ritchie et al. (1983) suggested that reduced neural drive by the central nervous system may be caused by central fatigue. Although maximal strength loading using the pneumatic resistance consisted of maximum effort, the higher acceleration and velocity generation at the beginning of the movement in the pneumatic loading may not be as stressful in inducing central fatigue as in the weight-stack loading with higher resistance in untrained individuals.

Three minutes rest between single maximal repetitions were enough to maintain the resting twitch force characteristics during pneumatic maximum strength loading, which is an indication of a recovered state of excitation-contraction coupling (Duchateau & Hainaut 1984). However, loading with weight-stack resistance induced progressive decreases in the state of excitation-contraction coupling after the first five repetitions, which might be linked to an impairment in calcium kinetics (Allen et al. 2008). In addition, maximal EMG and activation level decreased significantly ($p < 0.05$) due to maximum strength loading with weight-stack, but not due to pneumatic resistance loading. Time under maximal tension might explain part of the peripheral fatigue, since Behm et al. (2002) observed similar fatigue between 5, 10, and 20 repetitions during sets to failure. The resting twitch the first minute of between-set recovery is strongly and inversely linked to peripheral fatigue and post-activation potentiation (Tillin & Bishop, 2009). Increased recruitment of higher order motor units and the phosphorylation of myosin regulatory light chains are thought to be principal mechanisms behind post-activation potentiation (Hodgson et al. 2005; Chiu et al. 2003). During the 2nd and 3rd minute of rest the twitch force responses remained on the same level throughout the whole loading, even though the weight-stack loading caused a little bit stronger peripheral fatigue, which might be associated with greater rate of metabolic by-products.

6.1.2.2 Power loading

The power loadings using weight-stack with and without the additional elastic resistance induced reductions in isometric fast force production with limited effects on the high force-end of the force-time curve and MVC. Fast force production decreased by ~20 Δ%, whereas MVC decreased only by ~5 Δ%. Otherwise, the initial velocity during repetitions in power loading was significantly higher with pneumatic resistance compared to weight-stack. Regardless, the pneumatic resistance loading caused similar fatigue-induced decreases in force production and EMG as after maximum strength loading, but the magnitude was lower. Therefore, the reduction in the fast force production was specific to power loading on the weight-stack resistance, probably due to the effect of the inertia. Also, pure weight-stack resistance loading appeared to specifically affect both force production and EMG during the first 100 ms to a greater extent than weight-stack with elastic resistance, although EMG decreased (~10 Δ%) parallel with MVC in both weight-stack power loadings.

It is well known that fatigue is task-dependent (Gandevia, 2001), and a larger decrease in maximal force is usually also linked to a reduction in rapid force production. Conversely, the results of the resting twitch responses during recovery between sets, showed that power loading with pneumatic resistance induce slightly more peripheral fatigue and (probably) specifically in fast motor units due to higher contraction velocities compared to explosive repetitions in weight-stack resistance (Hamada et al. 2003). Interestingly, power loading using weight-stack resistance caused acute decreases in rapid torque production without dramatic concomitant changes in maximal torque production. Otherwise, smaller central fatigue on the weight-stack only compared to greater resistance with combined weight-stack and elastic resistance, is in-line with previous studies of high volume explosive jumping (Drinkwater et al. 2009; Strojnik & Komi 1998). Additional elastic resistance in the power loading caused partly similar fatigue as maximal strength loading. In other words, pure weight-stack and inertia resistance alone would appear to be more specific to ballistic-type power training compared to resistance modes that continuously "brake" throughout the movement , as in pneumatic and elastic resistances. Thus, it could be speculated that the rate of motor unit recruitment may then have been compromised for specific needs of each resistance mode with significant individual differences.

Muscular power is used also as one of the main parameters in the measurement of explosive athletic performance, and several studies have used power or its components (torque and angular velocity) to indicate fatigue due to different kinds of power loadings (e.g., Cormie et al. 2011; Kawamori & Haff 2004). Typical power loading (e.g. 5 × 5 × 40% 1RM) using pure weight-stack caused decreases in angular velocity between 120 and 160° knee joint angle, which led to decreased power at 120–140° joint angles at the end of the loading. As may have been expected, due to greater resistance and total work done during weight-stack with the elastic resistance, greater reductions were observed in concentric torque, angular velocity, and power. In the weight-stack with elastic band resistance, decreased angular velocity and power were observed between 80 and 160° knee joint angles at the end of the power loading. Additionally, concentric torque decreased between 80 and 120° joint angles, which was not observed during loading using weight-stack only. The close pattern between decreases in angular velocity and power during both with and without the elastic resistance in the weight-stack device suggests that decreased power production was largely dependent on the muscles' ability to contract at high velocities because of the moderate loads that were used (Kaneko et al. 1983).

6.1.2.3 Hypertrophic strength loading

Measurements during hypertrophic loading demonstrated similar fatigue-related isometric force decrements (-30–40 Δ%) throughout the whole force-time curve from fast force to maximal force production on both pneumatic and weight-stack resistance modes. The equal force decrement throughout the force-time curve might indicate fatigue in a wide range of motor units and contractile variables (Folland et al. 2014). In addition, the generally high volume load and short recoveries (2min) between sets during hypertrophic loading decreased force production probably due to similar metabolic fatigue between both pneumatic and pure weight-stack resistances, as assessed by blood lactate levels. Therefore, hypertrophic loading probably challenged also some of the slow motor units. Stronger peripheral fatigue could be a consequence of greater work done per repetition during weight-stack performance compared to pneumatic resistance. This supports the proposition by Häkkinen et al. (1988b) that an effective torque–angle relationship of the resistance mode provides subjects an opportunity to perform a wider range of motion with higher load, or that (fatigue-induced) failure to lift the load would require fewer repetitions.

Short (2 minutes) recoveries between sets with high loads puts a great stress on the peripheral level of the neuromuscular system, thus, it is also possible to speculate that enhanced neural drive, evidenced as increased EMG and voluntary activation levels, tries to compensate this enormous peripheral fatigue during loading (Babault et al. 2006; Bigland-Ritchie 1981; Bigland-Ritchie et al. 1986). Recently, Latella et al. (2017) observed similar compensation phenomenon also in the corticospinal level after exercises close to the point of momentary voluntary failure. This increased neural activity and decreased force production has been termed neuromuscular inefficiency (Deschenes et al. 2000). However, hypertrophic type of training causes acute intra-muscular swelling or a so called "pump" –effect, which might enhance electrically evoked force response via stiffer elastic properties of the muscle-tendon complex. Increased amount of metabolic by-products and hydrogen ion concentrations with challenged energy production could explain the depressed evoked force responses when power and maximum strength loadings were compared. Proton [H^+] accumulation is related to the decrease of muscle fiber conduction velocity and thus the greater decrease in RFD after hypertrophic loadings (Lindström et al. 1970; Methenitis et al. 2016). Behm et al. (2002) observed that even a 3-minute rest after one 10RM set was not enough for the peripheral properties to recover to their initial level when compared to a 5RM set.

6.1.2.4 Monitoring aspects of recovery time-course

From a monitoring point of view, the moment immediately after loading is almost "chaotic", when some parameters drop dramatically in seconds and some others maintain or even increase during the subsequent minutes. The results of experiments I and II are in-line with Bompa & Haff (2009, pp. 104), that after the cessation of loading the body does not immediately return to a state of rest. This thesis also supports the notion that the loadings (experiment I) and used resistance modes (experiments I and II) have an effect on the measured responses. In addition, also the order of the post-loading measurements and, thus, the time delay from the end of the last repetition affects the amount and direction of the responses. For example, the high volume and intensity hypertrophic workouts could challenge the CrP and glycolytic systems and lactate levels from finger-tip blood samples might increase until five minutes after loading, while the lactate concentration may decrease inside a muscle, already after exercise cessation. In addition, the glycolytic energy process increases muscle temperature, which might improve ionic transfer in the neuromuscular system, e.g. enhanced calcium transfer in post-activation potentiation. This improved ionic transfer may also increase EMG-amplitudes and voluntary activation levels after hypertrophic loadings (experiment I). On the other hand, the resting twitch responses were potentiated after sets in the loadings without exhaustion (e.g. the maximum strength and power loadings) and, thus, it could be speculated that the phosphorylation level of the regulatory light chain was potentiated during dozens of seconds after the sets (e.g. Fig. 29 and 31) (Moore & Stull 1984). Passive twitches potentiated set-by-set during power strength loadings, because post-activation potentiation is also linked to the exercise volume (Vandervoort et al. 1983). It also seems to be linked to intensity e.g. when comparing the present power strength loadings (5 × 5 × 40% 1RM) with the maximum strength loadings (15 × 1RM). However, loading-induced stress should be sufficient but not too exhaustive to allow post-activation potentiation to be observed (French et al. 2003; Vandervoort et al. 1983), as it probably was in the present hypertrophic loadings (5 × 10 × 80% 1RM, Fig. 33). The length of the recovery period naturally plays a role in this potentiation-fatigue relationship (Sale 2002), which highlights exhaustion after hypertrophic loadings. Cumulative peripheral fatigue due to hypertrophic loadings might be a consequence of a failure of action potential, excitation-contraction coupling and/or impairment of cross-bridge cycling.

In the cross-sectional experiments of the present thesis, the recovery protocol was standardized to take place in a sitting position in the devices throughout 30 minutes. This passive recovery may restrict the metabolic activity via ineffective blood flow and removal of metabolic by-products from muscles. In addition, this could also delay neural recovery (Bigland-Ritchie et al. 1986; Woods et al. 1987). Recovery of force and power production, as well as EMG amplitude and spectrum parameters are curve-linear, when the steepest recovery rates are during the first minutes after loading (Izquierdo et al. 2009). Generally, the recovery process is faster, if the sets are not performed to voluntary contraction failure. In addition, these sets without exhaustion were not critical for the improvement of strength and muscle size (Folland et al. 2017; Sampson & Groeller, 2016).

6.2 Monitoring of isometric parameters during strength training (III)

The results from experiment 3 showed specificity of different strength training modes, as has been presented by several previous studies (Häkkinen et al. 1985a, 1985b, Newton et al. 2006). Therefore, these results can be considered valid to investigate the possibility to monitor different strength training adaptations within the present study design. During the whole 20-week hypertrophic training period (HYP I+II periods), maximal (MVC) and fast (RFD 10ms) force production improved in parallel ($r = 0.45$-0.59), but this was not observed during the maximum strength and/or power training periods. The present results suggest that changes in peripheral structures/properties are dominant behind early improvement of isometric force production (MS and HYP I, 0-10 wk), but the latter improvements in fast force production seems to also require enhanced neural drive (EMGrms 0-100 ms 38 ± 45% and 0-500 ms 13 ± 48%) with power training (11-20 wk). In addition, the different training periods during the longitudinal training intervention with weight-stack resistance induced parallel changes in isometric RFD and MVC monitoring parameters, similarly to the same type of cross-sectional loading sessions with weight-stack resistance in this thesis.

6.2.1 Maximal voluntary contraction (MVC)

Maximal isometric peak force reflected both peripheral (e.g. CSA) and central (e.g. AL) qualities, but the observed correlations between the changes in MVC and CSA (MS-P, $r = 0.595$; HYP I-II, $r = 0.664$) cannot specify precisely how much the changes in isometric MVC were explained by increased muscle size or other factors (Fig. 2b). The study of Balshaw et al. (2017) showed that the changes in EMG and volume of the agonist muscles along with pre-training strength level explained ~60% of the changes in MVC during isometric training, whereas the changes in EMG explained ~30%, alone. Meijer et al. (2015) observed that both hypertrophic and strength-power type training improved isometric strength at the muscle fiber level, but only strength-power type training increased maximal force production per cross-sectional area of muscle fibers. The inverse relationship ($r = -0.84$, $p < 0.01$) between the changes in AL and CSA (Fig. 2a) due to 20 weeks of hypertrophic training also supports this view. Moreover, the positive correlation between the changes in MVC and AL during power training ($r = 0.65$, $p = 0.059$) and increased MF over the same training period ($10.4 \pm 21\%$), might also be a sign of improved activation strategies (Un et al. 2013) via explosive repetitions in power training.

The first 10 weeks during the maximum strength and hypertrophic training periods improved dynamic leg press 1RM ($11 \pm 6\%$ and $8 \pm 6\%$) and led to muscle hypertrophy ($7 \pm 10\%$ and $16 \pm 13\%$) in previously untrained subjects, although there were no statistical differences between these training modes. Likewise, Campos et al (2002) observed also similar increases in CSA after 8 weeks of training with these modes. Only hypertrophic training continued throughout the whole 20 weeks of training, which might decrease the inter-individual variability in the hypertrophic type-training group. Decreased inter-individual variability might explain the changes in the present study since isometric leg extension MVC correlated significantly with the leg press 1RM only between 10 to 20 weeks during hypertrophic training. Adequate training background of the subjects seems to be a common trait in previous studies, which observed strong correlation between isometric MVC and dynamic 1RM, e.g. in college football players (McGuigan & Winchester 2008) or in elite weightlifters (Haff et al. 2005).

During the isometric MVC, the internal structures of the muscle-tendon unit are under greater strain for a few seconds compared to stress during concentric contractions, generally. However, several long-lasting and rather slow muscle contractions at near-maximal or maximal level at the end of hypertrophic sets or just before the failure of the contractions match more closely maximal isometric stress level at each joint angle compared to explosive contractions

(Young & Bilby 1993). In addition, the increases in CSA due to hypertrophic training correlated negatively with neural adaptations, since there were impairments in AL and maximal EMG during MVC, both of these are contrary to MS-P training. The positive correlations between knee extension muscle isometric force production and CSA showed also two different training mode-specific adaptations for maximal force production over the whole training intervention, which supports the findings of the present study. In other words, increases in strength should not be used as a surrogate of muscle hypertrophy during monitoring of training as these different training modes led to different magnitudes of CSA but similar MVC increases.

6.2.2 Rate of force development (RFD)

The numerous multifaceted follow-up laboratory measurements of the present study support the use of RFD as the benchmark parameter for monitoring the training sessions. However, RFD seems to be sensitive for the testing position, because during the follow-up measurements, the changes of the force response over a single-joint due to electrical stimulation correlated only with isometric knee extension RFD, not with multi-joint leg extension RFD. Other agonist and synergist muscles and their complex activation strategies over several joints cause difficulties to identify training-based changes. This is because RFD is related, at least partly, to muscular properties including muscle size, fiber type and myosin heavy chain isoforms; and neural properties including recruitment pattern, muscle fiber conduction velocity, firing rate and synchronous firing of motor units (Hallet et al. 1975; Häkkinen et al. 1985b; Harridge et al. 1996; Methenitis et al. 2016). In addition, adaptations in the complex architectures of muscle and tendon-aponeurosis might explain early improvements of RFD without concomitant neural changes (Bojsen-Moller et al. 2005; Earp et al. 2011). The present correlation between resting twitch slope and RFD ($r = -0.45$, $p < 0.05$) support this speculation, at least partly. Unfortunately, specific changes in tendon-aponeurosis, pennation angles or fascicle lengths of different muscles were not measured in these studies of thesis. Nevertheless, the present training intervention study measured the CSA of VL muscle, which reflects a combination of changes in pennation angles and fascicle size.

The relationship between influences of the aforementioned contributory variables for RFD can change due to the different phase of the force-time curve and the length of the RFD window. In the present study, the time to reach peak RFD increased during hypertrophic training compared to maximum strength followed by power training. This is in-line with the study of Folland et al. (2014), which observed that neural variables play a major role in the early phase of the force-time curve, while contractile variables and maximal strength level are more responsible for later phases of the curve. The great volume of high resistance and slow velocity movement promote hypertrophy (Tesch 1992), but also may decrease maximal velocity of contraction due to the increase in fiber angle (Tesch

& Larson, 1982). Conversely, fast velocity isokinetic training (180°/s) seems to improve peak RFD (DeOliveira et al. 2013) without changes in the late phase of the curve and MVC. In the study of DeOliveira et al. (2013), peak RFD was reached around 30ms after the force onset, which was similar with the time to reach RFD during maximum strength and power training in the present study.

Moreover, the adaptations in muscle activation during dynamic contraction seems to be specific for maximum strength and power training, which might partly explain improvements in RFD via enhanced muscle activation during the power training period. Therefore, both central and peripheral properties play an important role in isometric RFD during the steepest 10ms window of the force-time curve. Nevertheless, it should be remembered that the training program was not fully optimized to increase RFD in the present measurement setting, rather it was planned to improve maximum strength and power production, generally. For example, in the study of Tillin et al. (2012), subjects improved their first 50ms RFD during 4 weeks by 54%, when they trained explosive unilateral isometric knee extension contractions 4 times per week with the measurement device.

6.3 Individual differences in improvement of RFD due to strength training (IV)

Experiment 4 emphasized highly individual enhancements in the RFD, even though the strength training program was the same for all subjects with similar relative training volumes. Previously, the changes in RFD were closely associated to various neuromuscular adaptations in both peripheral and central parts of the neuromuscular system (Maffiuletti et al. 2016) and, thus, in experiment 4, RFD was selected as a criterion to categorize subjects into sub-groups. The periodized strength training intervention was designed in order to improve both maximal and explosive force production, because these qualities have been observed to affect RFD in earlier studies (Häkkinen et al. 1985a, 1985b). In addition, it is well established, that maximal strength and rapid force production are closely related (Andersen et al. 2010) and, thus, offers an alternative stimuli to a common strength training target. One previously used method is that RFD was normalized to MVC but one should remember, that at least during power strength training, MVC might even decrease and, thus, normalized RFD may lead to misinterpretations e.g. with plateaued RFD. In the present study, MVC normalized RFD results indicated that e.g. the size of muscle tissue and other peripheral factors (twitch force) are not crucial for relative enhancements in rapid force production, as was observed when comparing the monitoring data of MS- and P-responders vs. Non-responders.

Responders versus Non-responders. The initial levels of dynamic 1RM leg press and CSA of VL were similar between the MS- and P-responders; however, 1RM and muscle size were lower in Non-responders. This parallelism is logical, because a strong association between maximal strength and CSA was observed during experiment 3 and in several other studies. For example, Trezise et al. (2016) calculated 0.46-0.59 ratios of the explained variance (R^2) between strength (isometric and concentric) and CSA depending on the displacement on the muscle. Subjects in the Non-responders group also had smaller (p = 0.019) free androgen index (FAI) compared to responders. All subjects increased their 1RM similarly throughout the maximum strength training period, although the adaptations in CSA were minor in Non-responders compared to both MS- and P-responders. Furthermore, responders' basal serum hormonal concentrations, such as total and free testosterone, and testosterone/cortisol and FAI–ratios were diminished (p = 0.01-0.03) during the maximum strength period, but this was not noticed in the Non-responder group. However, all subjects only maintained their CSA and 1RM levels during the following power strength training period. In all three groups, no systematic differences were observed between muscle activation during 1RM trials. Nevertheless, there were indications that neural deficit assessed by ITT, were greater (p = 0.06) in Non-responder subjects compared to the responder groups during isometric MVC after the first 10-week period of the training.

Responders. At the beginning of the whole training intervention, the MS-responder group had the greatest resting twitch (RT) force and RT force/time –ratio, compared to the other subjects. However, RT force and RT force/time –ratio in the P-responder group improved to the same level throughout the maximum strength period, while subjects in the Non-responder group only maintained their levels. This is also in-line with the study of Trezise et al. (2016), which observed that RT force levels explained approx. 1/3 of the maximal strength estimation. Interestingly, the MS-responder group had enhanced RT force/CSA –ratio that may indicate that the MS-responders had a more appropriate neuromuscular readiness to improve their power generation compared to the other groups. These observations might explain part of the mechanisms behind previous findings that stronger individuals possess more beneficial neuromuscular characteristics for superior enhancements in maximal power generation (Cormie et al. 2010; Cormie et al. 2011a; 2011b). The subjects in the MS-responder group increased their ability to effectively activate their increased muscle mass during dynamic explosive contraction as was observed by improved mean (p < 0.03) and peak (p = 0.07) power generation during the maximum strength period compared to the other groups.

In the measurements before and after 10 and 20 weeks of training in the present study, power determination was performed using 50% 1RM loads, which were defined from the measurements before the training intervention. Due to enhanced 1RM after 10 and 20 weeks training, these relatively lower loads possibly required the subjects to increase power generation via improved contraction velocities. Accordingly, it may be assumed that MS-responders possess enhanced peripheral 'readiness' to train, which might partly reflect their improved power generations. This observation is in-line with the results of Baker

(2001) who concluded that greater power generation requires adequate maximal strength levels before velocity-specific power enhancements could be revealed.

Non-responders. This study was not able to fully explain the origin of Non-responders' maladaptation to the training stimuli. Individually tailored training programs might cause more effective training effects and endocrine responses compared to generic training programs. Ahtiainen et al. (2016) showed that 29 % of traditional resistance trainees were low-responders based on muscle size, which is in-line with the number of Non-responders (~1/3) during maximal and power strength training in the present study. One limitation of the present study was that nutrition was not controlled. However, subjects were instructed to follow national nutrition recommendations with guidance on required protein intake for strength training. The initial training status of the subjects is complex and difficult to determine, even though they are untrained in terms of strength/resistance (Buckner et al. 2017). This might affect their improvement potential, but also the needed stimuli to produce desired adaptation. In addition, it should be remembered that the trainee's categorization based on parameters other than RFD might change individual classifications of the Non-responder and responder groups.

6.4 Strength training optimization based on monitored isometric parameters

6.4.1 Perspectives for training optimization based on improvement of RFD

From the training monitoring point of view, regular monitoring of a trainee's isometric force production capacities may assist in optimizing adaptation based on maximum strength-power profiling. Depending on the current training phase and periodization, the major focus for training should be qualities requiring improvements, and thus, correct monitoring parameters for those qualities (McGuigan 2017). Related to the training intervention in this thesis, the impairment of RFD at the end of the maximum strength followed by power training period could be a sign that the high intensity power training period continued too long and intensively and/or was too monotonous for optimal strength gains. In this example situation, regularly collected monitoring data is extremely valuable. Typically, power specific training periods last only for 2-6 weeks (Fleck & Kraemer 1987). Single maximum strength training sessions between power training did not offer an adequate alternative stimulus to progress improvement in monitored RFD or maintain AL, although these were able to maintain CSA and dynamic maximum strength levels a while longer. Nevertheless, Häkkinen et al. (2003) have shown that RFD could increase in parallel with MVC and 1RM also after 14 weeks of training, if the volume of maximum strength training is of a greater proportion to power training than in the present study. However, the study from Häkkinen et al (2003) used a longer analysis time window for RFD, which might explain a stronger association with maximum strength (Andersen & Aagaard 2006). Shorter RFD windows may have better functional validity in sport performances (Abernethy et al. 1995), but marginally reduce reliability (Wilson et al. 1993). However, monitoring feedback (e.g. the shape of isometric force-time or force-velocity curves) shows only what specific muscle outputs should be developed, not how this should be done (Morin & Samozino 2016).

From a training optimization perspective, enhanced neural properties via power training, as measured with EMG, become more dominant during the progression of training compared to the present stimuli from continuous hypertrophic training. Therefore, intensive strength training where power is combined with maximum strength can also, in some trainees, lead to a training plateau or even to a state of overreaching and/or early phases of overtraining. In the present training study, the decreased RFD and a descending trend of evoked resting twitch force response support this suggestion. Fry et al. (1994a; 1994b) observed that training-specific properties were impaired even though e.g. maximum strength levels were still maintained, when approaching the state of overtraining. The changes in AL support this and its significant positive correlation with peak power during power training, i.e. some subjects did not increase AL during the power training period and this may have influenced their lack of improvement in peak power (Fig. 36c; subjects A, B and D). In addition, muscle activity increased during maximal explosive force production both in isometric and dynamic contractions after power training, including also muscle activities at the onset of RFD determination trials. These results are in-line with a study from DeRuiter et al (2004), who showed a strong correlation between AL and initial EMG during fast knee extensions. Furthermore, Del Balso & Cafarelli (2007) showed a strong correlation between RFD and the rate of muscle activity due to progressive isometric training. During hypertrophic training, MVC and RFD changed similarly throughout the intervention, but these parameters were improved only during the first seven weeks in these previously untrained subjects.

6.4.2 Individual timing of increased RFD due to strength training

The present experiment 4 was a novel one, since it assessed separate training sessions during the training program and used its' differences in acute responses to identify mechanisms for individual adaptations. Greater training volume due to higher absolute training loads used in the gym, might create stronger stimuli for peripheral adaptations (e.g. CSA, RT parameters) to reflect alternative demands of the training modes between the Non-responder versus the MS- and P-responder groups. Although the overall training program and volume were the same in MS- and P-responders during the maximal strength training period, the perceived stress may have been optimal for some subjects, while it may have overtrained or undertrained others, e.g. depending on their training background and/or genetics of the individual. The blood lactate values observed in P-responders after the maximum strength exercises in leg press indicated a greater metabolic stress compared to Non-responders, where the anaerobic glycolytic system was challenged. This continued high stress might cause possible states of overreaching or even a low level of overtraining, which might explain the observed decreasing trend of anabolic hormone levels and both testosterone/cortisol and FAI -ratios parallel with a maladapted RFD (Fry & Kraemer 1997). It has been suggested that hormonal regulation may be one important factor for trainability (Häkkinen et al. 1985; Kraemer et al. 1990). Therefore, P-responders' delayed RFD improvement compared to MS-responders might be a consequence of their greater training-induced fatigue during every maximum strength training session. In other words, it is possible that maximum strength training induces such a high level of fatigue in these individuals that potential increases in performance are suppressed during monitoring measurements. Thus, power training offered a different training stimuli with a marked reduction in volume load (decreased to 60%), which might be more suitable for individuals in the P-responder group to realize training-induced RFD adaptations. Shepley et al. (1992) have shown an association between changes in training stress and hematological indices, e.g. approaching significant depression in hemoglobin and hematocrit levels during stressful training periods and recovery of these indices with high-intensity low-volume training as observed in P-responders compared to MS-responders (p = 0.056-0.08) in the present study.

In addition, the same depression was also observed in their muscular activity, which dropped (-22 ± 14%, p = 0.06) after the maximum strength period and recovered (57 ± 10%, p = 0.077) during the power strength training period at the first 20 degree joint angles in the power determination tests. This stagnation was specific only for explosive power production and not for 1RM, which might mainly represent depression of the fast motor units with low fatigue-resistance capacity and it may reflect a more non-functional fatigue or overreaching than overtraining state (Meeusen et al. 2012). Mujika et al. (2003) concluded that the effect of decreased training volume (decreased to 50-70%) for 7-21 days could result in increases in power production, depending on the individuals as well as their training programs and backgrounds. This might partly influence a delayed training effect (Zatsiorsky & Kraemer 2006, pp. 104) as observed in the RFD of P-responders. However, it seems that strength trainees can improve their low-velocity strength earlier (already after 8 days) than high-velocity strength properties after greatly reduced training volume (Gibala et al. 1994).

The aforementioned hormonal differences could also explain an "aggressive" effort to train, and thus reach greater power training-induced fatigue (Ryushi et al. 1988). In addition, Ahtiainen and Häkkinen (2009) showed that stronger individuals are capable of producing greater fatigue levels than their weaker counterparts, as was the case in Non-responders in the present study. Alternatively, the observed reduced fatigue after acute exercise, as well as an unchanged velocity component of power and RFD could be a sign of a greater distribution of slower muscle fibers in Non-responders. In addition, greater testosterone levels were related to a greater portion of fast muscle fibers and these both correlated positively with training-induced changes in fast force production (Häkkinen et al. 1985b, 1990). These assumptions are perhaps best supported by lower responses of muscle stimulation-induced RT –parameters, because this method primarily activates superficial muscle fibers and, thus, mainly larger motor units (Knight & Kamen 2005; Stuart et al. 1988).

7 CONCLUSIONS

1) The resistance-joint angle -curve with pneumatic resistance and weight-stack with and without elastic resistance is different and can effect trainees' muscle activities, torque production, generated angular velocity and power production during a single repetition. In addition, repeated contractions can induce specific fatigue profiles and training responses from the same training protocol. Therefore, it is recommended that the most effective resistance mode should be chosen according to the individual's specific training goal.

2) Exact time points for monitoring recovery between sets and after loading should be strictly controlled, because recovery rates were not linear from the end of the last contraction throughout the 30 minutes of recovery, and not even during the first recovery minutes. Naturally, the shape of the recovery profile was affected by the preceded loading type, as well as the resistance mode used on the assessed monitoring variables.

3) Time to reach peak RFD could be a potential parameter to identify differences in "peripheral and central qualities" due to specific training adaptations between hypertrophic and maximum strength with followed power strength training. On the other hand, the steepest phase of the RFD curve may identify adaptations particularly during maximal strength/power training. Monitored isometric RFD parameters seem to more sensitively and systematically reflect short-term responses from different training stimuli compared to peak isometric MVC. Nevertheless, as one could expect, MVC seems to correlate with the long-term changes in 1RM due to strength training.

4) From the individual trainee's perspective, the timing of the improvement of monitored RFD was related to the increase in CSA and larger responses in anabolic and catabolic hormonal regulation. Regularly repeated isometric monitoring during strength training could assist in tailoring

training programs and selecting durations of the periodization cycles for each athlete, individually.

YHTEENVETO (FINNISH SUMMARY)

Voimaharjoittelun monitorointi isometristen voima-aika – muuttujien avulla sekä eri vastustapojen akuutit vaikutukset hermolihasjärjestelmän toimintaan

Tavoitteellinen harjoittelu vaatii systemaattista fyysisten ominaisuuksien seurantaa ja harjoitusohjelman uudelleen kohdentamista, mikäli odotettua edistymistä ei tapahdu. Tätä kutsutaan harjoittelun monitoroinniksi ja harjoitusvaikutuksen optimoinniksi. Kestävyysharjoittelussa henkilökohtaisen harjoittelun ja harjoitusvaikutuksen seurantaa varten on markkinoilla ollut jo vuosikymmeniä tarjolla erilaisia laitteita ja sovelluksia kuten monipuolisia sykemittareita erilaisin algoritmein, pedometrejä, pyöräilytietokoneita ym. Sen sijaan kuntosaliharjoittelun seuranta perustuu edelleen hyvin pitkälti kynä/paperi -pohjaiseen harjoituspäiväkirjan pitoon, kuten tapana on ollut useita vuosikymmeniä. Tänä päivänä uudet miniatyyriteknologiat ja niiden jatkuva edullistuminen ovat mahdollistaneet uusien innovatiivisten monitorointisovellusten kehittämisen. Nämä anturit vaativat kuitenkin ymmärrystä kerätyistä muuttujista sekä kuinka ne kuvaavat voimaharjoittelun vaikutuksia. Eräs vaihtoehto on hyödyntää isometrisiä mittauksia kuntoilulaitteisiin kiinteästi asennetuilla tai harjoittelijakohtaisilla antureilla. Isometriset testit ovat osoittautuneet helposti standardoitaviksi ja suoritustekniikaltaan nopeasti opittaviksi sekä ne ovat turvallisempia maksimaalisissa suorituksissa kuin dynaamiset testit, myös väsytyksen jälkeen. Isometristen testien voidaan olettaa kuvaavan enemmän voimaharjoittelun yleisiä harjoitusvasteita ja adaptaatioita kuin spesifisten dynaamisten testien, vaikka harjoittelu itsessään olisikin dynaamista.

Useat aiemmat tutkimukset ovat selvittäneet voimaharjoittelussa eri suuruisten kuormien, toistomäärien sekä sarjapalautusten pituuden vaikutuksia harjoitusvasteisiin. Sen sijaan yksi olennainen tekijä harjoitustilanteesta on jäänyt aiemmin vähemmälle huomiolle – käytetyn vastustavan vaikutus.

Ensimmäinen osatutkimuksemme selvitti lihaskasvun, maksimivoiman ja nopeusvoiman kehittämiseen kohdennettujen harjoitteiden aikaisia sekä niiden jälkeisiä välittömiä vaikutuksia harjoittelijan fysiologiaan ja voimantuottoon, niin ilmapaine- kuin painopakkavastuksellisilla kuntosalilaitteilla. Kyseiset vastustavat ovat yleisimpiä kaupallisilla kuntosaleilla olevissa laitteissa. Vastustapojen erot kiteytyvät niiden erilaisiin inertiaominaisuuksiin. Tutkimuksemme osoitti, että painopakkavastus aiheutti suuremman hermostollisen ja lihasperäisen väsymyksen lihaskasvuun ja maksimivoimaan kohdistetuissa harjoitteissa, mahdollisesti suuremmasta kokonaistyömäärästä johtuen kyseisellä laitteella. Nopeusvoimaharjoite inertiaa hyödyntävällä vastuksella vaikuttaa merkittävästi nopeaan voimantuotto-ominaisuuteen, kun taas ilmanpainevastuksesta saattaa olla hyötyä voimantuoton kehittämiseen suurilla liikenopeuksilla ja tavoiteltaessa suurta tehon tuottoa.

Toisessa osatutkimuksessa selvitimme voidaanko nopeusvoimaharjoitteen harjoitusvaikutus kohdistaa sekä nopean voimantuoton ominaisuuteen, että maksimivoimaan silloin kun painopakkavastukseen on yhdistetty elastinen lisävastus (vastuskumi). Elastisen lisävastuksen huomattiin kuitenkin vähentävän nopeaan voimantuottoon kohdistuvaa hermostollista vaikutusta suuremman kokonaisväsymyksen myötä, ilman systemaattista voimaharjoittelutaustaa olevilla koehenkilöillä.

Näiden poikittaistutkimusten lisäksi isometrisiä muuttujia käytettiin monitoroimaan harjoittelun adaptaatioita 20-viikon lihaskasvuun tai 10-viikon maksimivoimaan ja sitä seuraavaan 10-viikon nopeusvoimaan tähtäävien harjoitteluiden myötä. Monitoroitavina isometrisinä muuttujina olivat maksimivoima (MVC), voimantuottonopeus (RFD) ja aika maksimaalisen voimantuottonopeuden saavuttamiseen. Monitorointi tapahtui isometrisellä jalkaprässillä joka 7. harjoituskerran aluksi eli 3½ viikon välein. Tämän jälkeen koehenkilöt tekivät harjoitusohjelman mukaisen dynaamisen jalkaprässiharjoituksen, jonka akuuttia väsymysvaikutusta voimantuottoon monitorointiin samalla isometrisellä laitteella. Lihaskasvuun tähtäävä harjoittelu paransi voimantuottonopeutta ainoastaan ensimmäisen seitsemän viikon aikana ja voimantuottonopeuden muutos oli koko harjoitusjakson ajan yhtenevä maksimivoiman muutoksen kanssa. Sen sijaan maksimivoimaharjoittelu jaksotettuna nopeusvoimaharjoitteluun paransi voimantuottonopeutta 17 viikon ajan, maksimivoimasta riippumatta. Lihaskasvuun tähtäävässä harjoittelussa aika maksimaalisen voimantuottonopeuden saavuttamiseen hidastui verrattaessa maksimi-nopeusvoimaharjoitteluun. Monitoroinnin tulee käytännössä kohdistua yksittäisen harjoittelijan edistymisen seurantaan, toisaalta tieteellinen näyttö vaatii systemaattisuutta. Tämän vuoksi tutkimme yksittäisten maksimivoimaa (MS) ja sitä seurannutta nopeusvoimaa (P) harjoitelleiden henkilöiden kehittymistä, josta pystyimme identifioimaan harjoittelijat kolmeen alaryhmään; MS-responderit joiden RFD parani maksimivoimaharjoittelun myötä, P-responderit joiden RFD parani nopeusvoimaharjoittelun myötä sekä Ei-responderit joiden RFD ei parantunut. Ei-responderit olivat alussa muita heikompia, heillä oli vähemmän lihasmassaa ja heidän hormonaalinen profiilinsa poikkesi muista ryhmistä. Ei-responderit pystyivät kuitenkin kasvattamaan maksimivoimaansa suhteellisesti saman verran kuin muidenkin ryhmien harjoittelijat. MS ja P-responderit olivat ominaisuuksiltaan lähempänä toisiaan, mutta maksimivoimaharjoittelun kuormittavuus saattoi häiritä ja viivästyttää RFD-muuttujan mukaista edistymistä P-respondereilla. Tämä kävi ilmi myös akuutin väsymyksen monitoroinnista. Harjoitusvolyymin väheneminen nopeusvoimajaksolla toi esiin myös P-respondereiden kehittyneet nopeusvoimaominaisuudet. Yleisesti voidaan sanoa, että RFD-muuttujat ovat herkkiä nopean voimantuoton ominaisuuksien monitorointiin, kun taas MVC kuvaa yleistä maksimaalista voimantuottokykyä vasta systemaattisemmin voimaharjoitelleilla henkilöillä.

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ORIGINAL PAPERS

I

NEUROMUSCULAR RESPONSES TO DIFFERENT RESISTANCE LOADING PROTOCOLS USING PNEUMATIC AND WEIGHT STACK DEVICES

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Neuromuscular responses to different resistance loading protocols using pneumatic and weight stack devices

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ABSTRACT

The purpose of this study was to examine single repetition characteristics and acute neuromuscular responses to typical hypertrophic (HL), maximal strength (MSL), and power (PL) loadings performed with two of the most common resistance modes; pneumatic and weight stack. Acute responses were assessed by measuring maximal voluntary contraction (MVC), corresponding quadriceps-EMG and resting and superimposed twitch torques. Activation level was calculated from the twitch torques.

Decreases in MVC were greater during HL and MSL than during PL. During HL, resting twitch force decreased 8% ($P < 0.05$) more on the weight stack than on the pneumatic device. Furthermore, loading using the weight stack caused reduced resting twitch force, activation level, and EMG-amplitude after MSL and PL ($P < 0.05$–0.01).

PL on the pneumatic device decreased MVC and rapid force production, while the respective PL on the weight stack device was specific to decreased rapid force production only. However, mean angular velocities and power of the repetitions were higher on the pneumatic device when using light loads.

The present study showed that, at least in untrained subjects, the weight stack device induced greater levels of peripheral fatigue during HL. It also led to large central fatigue during MSL and PL. On the other hand, on the pneumatic device contraction velocity with low loads was higher compared to the weight stack device.

Therefore, it is recommended that the resistance mode should be chosen according to the specific training goal.

1. Introduction

The most widespread resistance modes of various training devices used in commercial gyms are pneumatic and weight stack. The resistance generated by pneumatic devices is proportional to the air pressure in the cylinder and can be modified by lever arms of the structure, whereas the device frame provides only a minimal contribution to the total resistance (see Frost et al., 2010). The resistance in the pneumatic cylinder is constant throughout the range of motion and is independent of contraction velocity. Conversely, the resistance provided by weight stack devices is composed almost entirely of mass, and is thereby influenced by inertia and momentum. As a result, the actual load (as sensed by the individual) is not maintained throughout the range of motion. With cam and lever arms of the device frame it is possible to customize the resistance and modify it to conform to the human torque-joint angle relationship. This is called variable resistance. Well designed variable resistance stresses the neuromuscular system over the entire range of movement (Graves et al., 1989). Torque production capabilities are well known to be partly dependent on the joint angle (Singh and Karpovich, 1966) and contraction velocity (Komi, 1973). However, contraction velocities and momentum affect forces exerted on the neuromuscular system, and should be considered to evaluate device properties. Häkkinen et al. (1987, 1988b) investigated weight stack devices with variable resistance and Frost et al. (2008) have studied pneumatic resistance repetitions with different velocities and loads and also muscular activities during the trials. Nevertheless, the differences between various resistance modes has not been investigated comprehensively using different strength training loading schemes (e.g. maximal strength, muscle hypertrophy and power).

Various strength training goals require specific loadings to achieve the desired adaptation. Development and adaptation progress due to fatigue, which will generate supercompensation (Zatsiorsky and Kraemer, 2006). The origin of fatigue has been classified as either central or peripheral (Bigland-Ritchie et al., 1978). In general, single session strength loading leads to acute fatigue observed as reduced force production, which is accompanied by acute neural, metabolic, and/or hormonal changes in the body if the exercise has been of sufficient intensity and duration. The exact responses relate to the specific type of loading (e.g. hypertrophic

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loading). However, if there are differences between devices in terms of how the resistance is produced throughout the range of motion, there may be differing amounts of work, muscle tension, and, therefore, muscle activity and rate of total work. Frost et al. (2010) suggested this possibility but to our knowledge no authors have directly compared these devices.

It is well known that the amount of work done plays an important role with working intensity and recovery phases in generating muscle growth (Patterson et al., 1985; Kraemer et al., 1990; Fitts and Widrick, 1996; Wernbom et al., 2007), which is the goal of hypertrophic training. On the other hand, higher movement velocities are possible when there is a difference between the resistance force and maximal force production capabilities of the muscles. Thus, this permits primarily high velocity improvements due to high velocity repetitions, for example, in ballistic or power training (Komi and Tesch, 1979; Häkkinen et al., 1985; Sale, 1988). Neural properties may also be developed through high loads, as in maximal strength training, where most or all of the motor units are required to produce large forces throughout the range of motion. Maximal strength training is based on the development of both neural properties and hypertrophy.

The purpose of this study was to examine acute neuromuscular fatigue after hypertrophic, maximal strength, and power loadings performed with pneumatic versus weight stack devices. Single repetition loading characteristics were also studied in order to reveal possible differences between the loading devices, which could then explain, at least, partly the differences between the acute responses.

2. Methods

2.1. Subjects

Fifteen healthy young men (20–35 years) volunteered as subjects. None of the subjects had regular strength training background but they were all physically active. Full details about possible risks or discomfort were given to the subjects and they signed the informed consent. The study was performed in accordance with the Declaration of Helsinki 1975, and protocol was accepted by the Ethics Committee of the University of Jyväskylä.

2.2. Experimental design and loading devices

The experimental design comprised a familiarization session with single repetitions and six different loading sessions: (1) maximum strength loading, (2) hypertrophic loading, and (3) power loading using both weight stack and pneumatic devices. After the familiarization session subjects rested at least 4 d before the first testing session. The loadings and the order of the devices were randomized and recovery times between the different loadings were at least 1 week. However, the power and hypertrophic loadings were performed on the same day and the hypertrophic loading was done one hour after the end of the power loading.

Subjects performed single explosive repetitions with different loads and performed three different resistance training sessions using bilateral pneumatic (P) (Hur 3350, Hur Ltd., Finland) and weight stack (WS) resistance (D200, David Sports Ltd., Finland) knee extensor devices in a seated position. Although the inertial characteristics of the resistance differ between the devices, they both provide variable resistance; the pneumatic system included lever arms and the weight stack system utilized a cam wheel in the mechanism. The range of the knee extension was 60–180° of knee joint angles and the hip joint angle was fixed, secured by a belt, to 110° throughout the movement. The knee extension exercise was chosen in the interests of using muscle stimulation and limiting the complexity of the model being examined, because this single joint movement isolated the quadriceps muscles. Also, different knee extension devices are very popular in commercial gyms.

2.3. Familiarization and single repetitions

The first session was partly a familiarization visit. In this session subjects practiced all the devices and each device was set up according to the above mentioned anatomical dimensions of the subject. Subsequently, one repetition maximum (RM) load was determined on both devices and subjects performed explosive single repetitions using 20%, 40%, 60% and 80% 1 RM loads in a randomized order. The 1 RM load was the highest load that each subject could use to complete a single repetition using an acceptable lifting technique. It was determined separately on both devices. Surface EMG, force and angle data were measured during all single repetitions. When analyzing the measurements of the familiarization session, all single repetitions were divided into six 20° sectors, from 60° to full extension (180°) of the knee joint angle. EMG activity of the vastus lateralis, vastus medialis and rectus femoris of the right leg were combined and averaged during analysis of single repetitions.

2.4. Loadings

In every loading session subjects performed a warm-up, which consisted of 6 reps on 40% 1 RM on the loading device. The maximum strength loading protocol consisted of 15 sets of one repetition at 100% 1 RM, with a 3-min rest period between the sets. The hypertrophic protocol was $5 \times 10 \times 80\%$ 1 RM, with a 2-min recovery. During these loadings the subject was just able to finish the required repetition of each set and the knee extension was done using a self-selected velocity. The power loading protocol consisted of 5 sets of 5 repetitions at 40% 1 RM load, with a 3-min recovery and each repetition was performed as fast as possible. All protocols were modified from Fleck and Kraemer (2004). All intensities were based on the device-specific maximum (1 RM).

2.5. Measurements

The measurements (pre- and post-loading) consisted of fingertip blood samples for lactate analysis, unilateral maximal isometric torque (MVC), resting twitch torque, and superimposed twitch torque during MVC at 107° knee angle (SMVC). Superimposed twitches (the protocol included also resting twitch), MVCs and blood lactate were measured immediately after the loadings (Fig. 1). Subjects were instructed to perform MVCs (without superimposed twitch) as fast as possible against the immovable load.

2.6. Force and angle

Both loading devices were equipped with in–built knee extension force and knee angle sensors allowing evaluation of concentric actions. The other torque measurements (pre- and post-loading) were performed on a separate isometric knee extension dynamometer (Department of Biology of Physical Activity, University of Jyväskylä). Consequently, the effects of both resistance modes on isometric contraction capability could be directly compared. In addition, a separate knee goniometer was attached to the leg around the knee joint and recorded knee joint angles during all dynamic repetitions. Calibration of all equipment was accomplished before the beginning of each test.

All torque (concentric and isometric) and angle signals were sampled at 2000 Hz and signals were low pass filtered (torque 20 Hz, and angle 75 Hz). From these parameters, mean angular

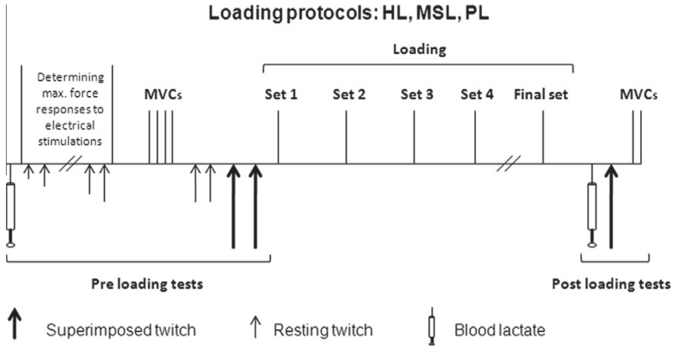

Fig. 1. Loading protocol; HL = Hypertrophic loading, MSL = Maximum strength loading, PL = Power loading, MVC = Maximal voluntary contraction.

velocity, mean accelerations and mean power (torque × angular velocity) values during single concentric repetitions were analyzed in 20° segments. Mean power was calculated as the mean angular velocity multiplied by the mean torque for each sector separately. Both before and after loading, the plateau of isometric MVC was used to determine mean maximal torque in 250 ms time window. The rates of torque development during the initial 100 ms were analyzed from the fastest MVC trials before and after loading, which were measured separately from the other MVCs with superimposed twitches (SMVC). In analysis, the definition of the start of contraction was based on the first sharp increase in force signal.

2.7. Muscle stimulation

Four carbon film muscle stimulation electrodes (V-Trodes, Mettler Electronics Corp., USA; diameter 70 mm) were arranged to the mid and distal portion of the quadriceps muscle group. Stimulation electrode pairs were galvanically separated and skin under the electrodes was shaved and cleaned.

Isometric knee extension torque responses due to electrical stimulation of resting muscle (resting stimulation) were determined at the 107° knee angle on the isometric dynamometer. The current was increased progressively in 50 mA steps after every stimulation when the torque response was higher than that of previous stimulation. When the maximal torque response was reached, 25% of the stimulation current was added. This supramaximal stimulus (125%) was used for all subsequent stimulations. The electrical stimulator (Digitimer Ltd., Model DS7AH, UK) produced single rectangular pulses (length; 200 μs).

Resting stimulations were performed two times with 1 min between the twitches. Twitch torque was analyzed from each twitch to determine the state of peripheral fatigue (Bigland-Ritchie et al., 1978). In contrast, central fatigue as assessed by the superimposed twitch protocol (Merton, 1954; Harridge et al., 1999) included resting twitches before and after SMVC and one twitch was delivered during the plateau phase of SMVC. The subjects were able to reach SMVC within 5 s and they were directed to increase their torque progressively towards the maximum and to avoid brief torque peaks. Voluntary activation level was measured and calculated from the superimposed twitch protocol according to the formula by Harridge et al. (1999):

$$\text{Activation level } (\%) = [1 - (P_{ts}/P_t)] \times 100$$

where P_{ts} is the difference between the voluntary torque and twitch torque from the superimposed twitch, and P_t is the resting twitch torque after SMVC.

2.8. Electromyography

Electromyographic activity (EMG) of the vastus lateralis (VL), vastus medialis (VM) and rectus femoris (RF) muscles during knee extension was recorded (Telemyo 2400R, Noraxon, USA) from the right leg using bipolar surface electrodes of 10 mm diameter with a 20 mm inter-electrode distance. The electrodes were placed according to SENIAM (Hermens et al., 1999). The placements of the electrodes were tattooed with small ink dots before skin preparation. The tattoos ensured that electrodes were on the same location of the muscle during all loadings. Raw surface EMG signals were sampled at 2000 Hz and they were amplified (500 gain) at a bandwidth of 10–500 Hz for later analysis. Signals passed through an analog-to-digital (A/D) board converter (Power 1401) to a computer using Signal 2.16 software (Cambridge Electronic Design, UK). After A/D conversion EMG signal data was bandpass filtered (20–350 Hz) and then transformed to root mean square (rms) form before being normalized based on isometric MVC values. However, EMG signals from explosive single repetitions were transformed to rms form without normalization, because all data was collected during the same session. Maximal EMG activity was analyzed during the plateau phase around the peak isometric torque from MVC over a 250 ms time window.

EMG activities of the vastus lateralis, vastus medialis and rectus femoris muscles were combined and averaged. Rectus femoris muscle activity was not measured during any of the resistance training sessions, because of the muscle stimulation electrodes.

2.9. Blood collection

Fingertip blood samples were taken to determine capillary blood lactate levels before the warm-up and immediately after the loadings. Blood samples were collected with 20 μL capillary tubes and mixed with 1 mL hemolyzing solution. Automatic blood lactate analysis (EKF Diagnostic, Biosen, Germany) was performed after testing.

2.10. Statistical analyses

The results are presented as means and standard deviations in the text. The angle-related effects in EMGrms and torque values were assessed by using a two-way ANOVA (time × device) with repeated measures. When a significant *F*-value was observed, Bonferroni post hoc procedures were performed to locate the pair-wise differences. The statistical comparisons of mean angular velocity and mean power with different loads were analyzed with a paired two-tailed student's *t*-test between resistance modes from single repetitions. The pre-post testing session comparison and their relative changes were also analyzed with a paired two-tailed student's *t*-test between different loadings and resistance modes. Statistical significance was accepted at a level of $P < 0.05$.

3. Results

3.1. Maximal and explosive single repetitions

In the torque–angle relationships, the greatest concentric torques (1085 ± 157 Nm (WS) and 825 ± 188 N (P)) were reached at between 100–120° knee joint flexion angles on the weight stack and 120–140° on the pneumatic resistance. The torque–angle relationships between the devices were significantly different ($P < 0.001$ and 0.05) at all knee extension angles from 60° to 160° on 1 RM loads (Fig. 2a). Using all submaximal loads, the weight stack caused greater resistance from 60–100° and the pneumatic device caused greater resistance at 160–180° knee joint angles ($P < 0.05$–0.001). Muscular activity of quadriceps muscles [(VL + VM + RF)/3] was initially (60–80°) higher ($P < 0.05$–0.01) during 20–60% 1 RM load on the pneumatic than on the weight stack device (Fig. 2b). However mean angular velocities decreased and duration of the contraction increased on both devices (Fig. 2c) when the load was increased. The contraction times were significantly ($P < 0.001$) shorter on the pneumatic device, when 20%, 40% or 60% of 1 RM loads were compared to the same loads on the weight stack device. Angular velocities increased significantly ($P < 0.001$–0.05) between the knee joint angles of 60–140° on the weight stack device with all loads, but angular velocities did not change during these knee angles on the pneumatic device. At the beginning of the movement at knee joint angles between 60–80° accelerations were 4–10 times greater ($P < 0.001$) on the pneumatic device than on the weight stack device at all loads.

Mean power was significantly higher ($P < 0.001$–0.05) during the 20% and 40% 1 RM repetitions on the pneumatic device (1009 ± 232 W/891 ± 362 W) in comparison to the weight stack device (436 ± 229 W/664 ± 289 W). The subjects reached higher ($P < 0.001$) mean power values on the weight stack device (9 ± 3 W) than on the pneumatic device (3 ± 2 W) only during repetitions performed with 100% 1 RM (Fig. 2d).

3.2. Loadings

Blood lactate levels increased after the hypertrophic loading on both devices without any statistical differences between the devices. Blood lactate concentrations were 9.5 ± 1.2 mmol/l on the pneumatic device and 10.0 ± 1.0 mmol/l on the weight stack device immediately after the loadings. The maximum strength and power loadings did not lead to a significant increase in blood lactate concentrations at the post-loading.

The isometric torque during MVC decreased significantly ($P < 0.05$–0.001) after all loadings (except power loading on the WS) on both devices (Fig. 3). The reduction in MVC was significantly ($P < 0.05$) greater on the pneumatic device (−13 ± 9%) than on the weight stack device (−5 ± 12%) during power loading. The hypertrophic loading decreased MVC more than the other two loading modes ($P < 0.05$–0.001), however, the differences between maximum strength and power loadings on the pneumatic device were not statistically significant. The rate of torque production decreased significantly ($P < 0.001$–0.01) after every loading on both

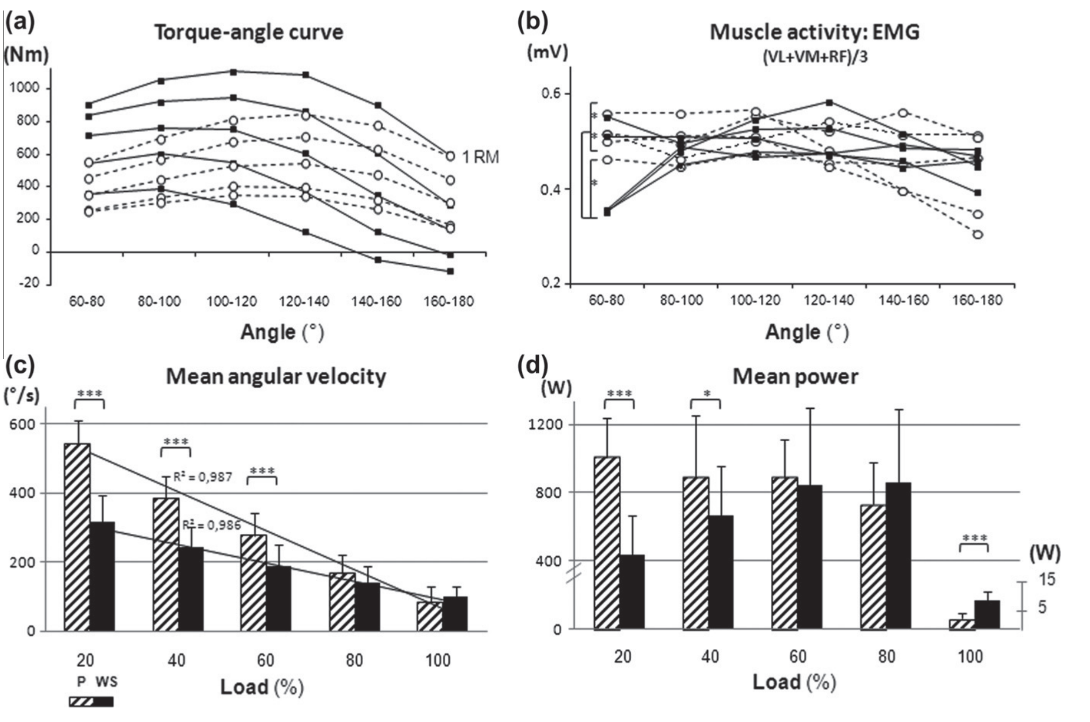

Fig. 2. (a) Torque–angle curve, (b) Muscle activity, (c) Mean angular velocity and (d) Mean power during single explosive (20%, 40%, 60%, 80% 1 RM) and maximal (1 RM) repetitions. $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$, P = pneumatic device, WS = weight stack device.

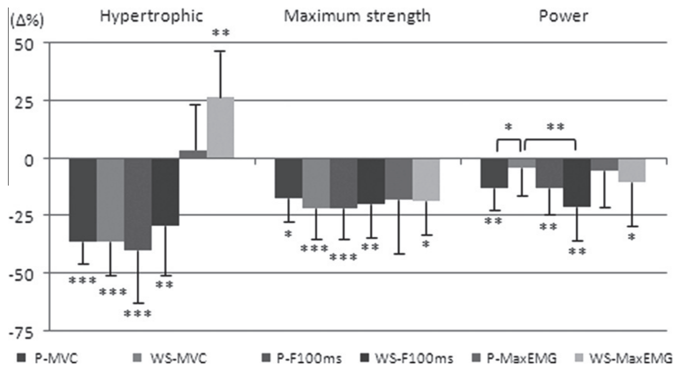

Fig. 3. Relative changes (pre to post 0) in maximal isometric MVC; P-MVC = isometric MVC on the pneumatic device, WS-MVC = isometric MVC on the weight stack device, P-F100 ms = force at the 100 ms on the pneumatic device, WS-F100 ms = force at the 100 ms on the weight stack device, P-MaxEMG = maximal EMG ((VL + VM)/2) on the pneumatic device and WS-MaxEMG = maximal EMG ((VL + VM)/2) on the weight stack device. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

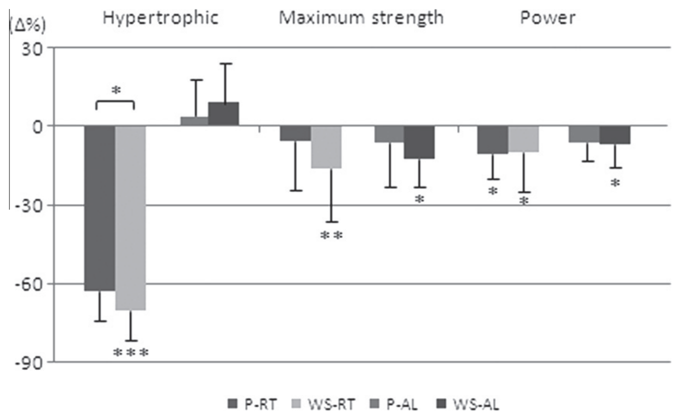

Fig. 4. Relative changes (pre to post 0) in resting twitch and superimposed twitch; P-RT = resting twitch on the pneumatic device, WS-RT = resting twitch on the weight stack device, P-AL = activation level on the pneumatic device and WS-AL = activation level on the weight stack device. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

devices. Reduction in the rate of torque production during 100 ms took place without significant decrease in maximal torque only during the power loading on the weight stack device ($P < 0.01$).

Resting twitch torque decreased significantly ($P < 0.001$) on both devices after the hypertrophic loadings (−71 ± 11% (WS) and −63 ± 11% (P)), but changes were larger on the weight stack than on the pneumatic device ($P < 0.05$). After the maximum strength loading resting twitch torque decreased significantly ($P < 0.01$) only on the weight stack device (−17 ± 20%) without significant differences between the devices. Power loadings induced significant ($P < 0.05$–0.01) changes in the resting twitch torque during both devices (−11 ± 15% (WS) and −11 ± 10% (P)) (Fig. 4).

Activation level decreased significantly ($P < 0.05$) after the maximum strength (−13 ± 10%) and power loadings (−8 ± 9%) on the weight stack device. On the pneumatic device the decreased activation level was not statistically significant during these loadings. Immediately after the hypertrophic loadings activation levels increased slightly, but without any significant differences between the devices (Fig. 4).

Maximal EMGrms decreased significantly ($P < 0.05$) after the maximal strength (−19 ± 14%) and power (−11 ± 19%) loadings on the weight stack device, but not on the pneumatic device. In line with the activation level, the weight stack device induced significant ($P < 0.01$) increases in maximal EMGrms immediately after the hypertrophic loading, but changes were not significant on the pneumatic device (Fig. 3).

4. Discussion

The present study showed that (1) the decreases in maximal isometric torque were greater after the hypertrophic and maximum strength loadings compared to the power loading on both variable resistance devices. However, (2) the reduction in the rate of torque production was specific to rapid actions following the weight stack power loading. On the other hand, the reduction of maximal isometric torque was greater after power loading on the pneumatic device than weight stack device. The results also showed that (3) peripheral fatigue as assessed by the resting twitch torque, was greater using the weight stack device compared to the pneumatic device following the hypertrophic loading.

These findings may have resulted from the greater resistance from around 60° to 160° knee joint angles, and therefore, higher muscular tension, while using the weight stack device with the 1 RM load. On the weight stack device the torque–angle relationship corresponded to maximal torque production capacities of the subjects and, thus, matched with natural torque–angle relationship more closely than on the pneumatic device at the 1 RM load. The effects of inertia and momentum are minor when angular velocities are lower and the torque–angle curve depends mainly on the shape of the cam. Häkkinen et al. (1988b) proposed that an effective torque–angle relationship of the resistance modes provided subjects with an opportunity to perform a wider range of motion with higher load, or that (fatigue-induced) failure to lift the load would require fewer repetitions. Thereby, larger peripheral fatigue could be a consequence of greater work done per repetition during the hypertrophic and maximal strength loadings on the variable resistance weight stack device.

When using lighter loads and higher velocities of movement on the weight stack device, the greatest resistance occurs at the beginning of the movement. The momentum of the weight stack produced by the rapid acceleration phase overcomes the weight stack resistance and there is a dramatic reduction in resistance at large knee angles (e.g. 120–180°). Instead, the shape of the torque-joint angle curve remained the same when using different loads (e.g. 40%1 RM vs. 80%1 RM) with the pneumatic device. Furthermore, higher angular velocities were observed during the current study as theoretically described by Frost et al. (2010), contributing to higher mean power during explosive actions, and consequently greater reductions in isometric maximal force. It is well known that fatigue is task-dependent (Gandevia, 2001), and a larger decrease in maximal force is usually linked also to a reduction in rapid force production. Interestingly, in our study, power loading on the variable resistance weight stack device caused acute decreases in rapid torque production without concomitant changes in maximal torque production. This could indicate a higher contribution of central fatigue when using the weight stack device possibly due to greater inertial effect during dynamic action. Thus, it could be speculated that the rate of motor unit recruitment may then have been compromised.

Greater central fatigue as assessed by the activation level changes was mainly induced by the present variable resistance weight stack device during the present maximal strength and power loadings, which may also be due to the observed torque–angle curve. The decrease in activation level as well as the decrease in maximal EMGrms is in line with Häkkinen et al. (1988a) and Linnamo et al. (1998). Bigland-Ritchie et al. (1983) have suggested that reduced motor drive by the central nervous system may be caused by central fatigue. It appears that, although maximal strength and power loadings using the present pneumatic device consisted of maximum effort, the higher acceleration/velocity at the beginning of the movement may not be as effective in inducing central fatigue as the weight stack device's higher resistance in our untrained subjects. The benefits of higher maximal EMGrms activity during the initial part of 20–60% 1 RM loads and higher velocities that are repeatedly used during training may lead to specific long term velocity improvements (Häkkinen et al., 1985; Pereira and Gomes, 2003) on the pneumatic device. However, these features need to be studied in more detailed.

Previous studies have observed both increased (e.g. Ahtiainen and Häkkinen, 2009; McCaulley et al., 2009) and decreased (e.g. Ahtiainen et al., 2004) muscle activation after a typical hypertrophic loading. During intensive and prolonged exercise such as hypertrophic loading, at least two different processes exist that have been observed to affect the magnitude of EMG signal. Maximal EMG usually decreases due to fatigue, whereas increased muscle temperature (Merletti et al., 1984; Petrofsky and Lind, 1980) or motor unit synchronization (Person and Kudina, 1968) can increase EMG. In this study muscle activity was high immediately after the hypertrophic loading and then decreased below the initial level. Therefore, it could be concluded that both of these processes may have affected this outcome depending on the duration of recovery. Unfortunately, muscle temperature was not measured in this study. The present maximum strength and power loadings were not assumed to induce significant increase in muscle temperature since the volumes were lower and loadings were of interval types, even though they were maximal.

5. Conclusions

It appears that, at least in untrained subjects, exercise on variable resistance weight stack devices induces greater levels of peripheral fatigue than exercise on the variable resistance pneumatic device during a hypertrophic loading protocol and it also led to a larger central fatigue during maximal strength and power loadings. Power loading on the pneumatic device induced decreased maximal strength and rapid torque production, while the respective power loading on the weight stack device led to decreased rapid torque production only. Otherwise, mean angular velocities and mean power of the repetitions were higher on the pneumatic device when using light loads.

Therefore, it would be recommended that, the exercise device used, should be specifically chosen according to the given training goal. Because the variable resistance weight stack and the pneumatic devices have their own specific properties, these properties should be taken into account when applying exercise regimens, not only for exercise enthusiasts but especially for competitive athletes.

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II

NEUROMUSCULAR FATIGUE TO POWER LOADING USING A WEIGHT-STACK DEVICE FITTED WITH OR WITHOUT ADDITIONAL RUBBER BAND RESISTANCE

by

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III

ISOMETRIC PARAMETERS IN THE MONITORING OF MAXIMAL STRENGTH, POWER AND HYPERTROPHIC RESISTANCE-TRAINING

by

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Isometric parameters in the monitoring of maximal strength, power and hypertrophic resistance-training

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Abstract

This study monitored strength-training adaptations via isometric parameters throughout 2×10 weeks of hypertrophic (HYP I+II) or 10 weeks maximum strength (MS) followed by 10 weeks power (P) training with untrained controls. Trainees performed bilateral isometric leg press tests analyzed for peak force (MVC) and rate of force development (RFD) every 3.5-week. These parameters were compared to dynamic performance, voluntary and electrically-induced isometric contractions, muscle activity and cross-sectional area (CSA) in the laboratory before and after 10 and 20 weeks. RFD increased similarly during the first seven weeks (HYP I 44±53%; MS 48±55%, P<0.05), but RFD continued to increase up to 65±61% from baseline (P<0.01) only during P. These increases were concomitant with enhanced dynamic performances of 1RMs (HYP I 8±6%; MS 11±6%, P<0.001), and explosive repetitions during P (11±15%, P<0.05). Time to reach peak RFD differed (P<0.001) between HYP (mean 42±20ms) and MS-P (mean 31±12ms) groups due to training. The changes in MVC correlated with the changes in CSA during weeks 1-20 (HYP I+II r=0.664; MS-P r=0.595, P≤0.05), as well as changes in 1RM (r=0.724, P<0.05) during weeks 11-20 (HYP II). Muscle activity increased during MS and P only. Both MVC and RFD improvements reflected combinations of central and peripheral adaptations. RFD parameters may be effective tools to evaluate adaptations, particularly during maximal strength/power training, while MVC cannot distinguish between strength or muscle mass changes. RFD-monitoring gave important information regarding plateaus in RFD-improvement, which were observed in dynamic explosive performances after HYP II compared to P.

Keywords: RFD, MVC, strength training, monitoring

Introduction

Neuromuscular adaptations and effective development of strength properties require a systematic and progressively increasing stimulus from the training program, as well as adequate variations between these training stimuli using the principle of periodization (Rhea and Alderman 2004). An individual's background and characteristics of strength training goals vary remarkably, which can also cause unique needs from the training stimulus for progressive adaptations and performance enhancement. Thus, systematic monitoring of the trainee's performance can be necessary in order to increase knowledge about the trainee's current condition and responses to recent training stimuli (Wasserman et al. 2012). It is known that physiological response to the neuromuscular system differs between primarily peripherally-affecting hypertrophic (Häkkinen & Pakarinen 1995) versus a primarily centrally-affecting power training protocols (Linnamo et al. 2004). Maximum strength training combines these stimuli, at least, in the untrained population (Narici et al. 1989), and causes adaptation to both central and peripheral components. Quantifying different physiological aspects traditionally requires several sophisticated laboratory tools to identify the specific adaptations during training. However, the use of these tools is often expensive, complicated and rarely available in non-laboratory settings, which limits opportunities for systematic and frequent strength-training monitoring. This perspective creates a need to determine inexpensive and practical methods and parameters for monitoring in a gym training environment.

Generally, all dynamic monitoring tests for strength-training require (near) maximal voluntary contractions (e.g. based on load, velocity, repetitions) and the tests themselves demand mechanical work and cause fatigue. Thus, the implementation of such tests during training sessions might disturb the desirable effects of the overall training program. One benefit of tracking training-induced adaptations by isometric testing is that it causes minor muscle fatigue, so that the disturbance to the training session is smaller than after repeated dynamic contractions (Abernethy et al. 1995), even though the produced isometric torque can be similar or closely exceeds isotonic torque (Knapik et al. 1983). Several isometric tests that are widely used to track changes during dynamic training are based on observations of partial generality of strength properties between different contraction modes (Hortobagyi et al. 1989). However, extrapolating dynamic performance from isometric testing may be erroneous, because e.g. Baker et al. (1993) stated that the contributing mechanisms to enhanced dynamic strength appeared to be unrelated to the mechanisms in isometric strength.

Several studies (see Jones et al. 2008 for a review) have observed high correlations between strength and CSA of the muscle in individuals with different training status. Nevertheless, the steepness of the trendline slope may suggest differing contributions of CSA and other factors to overall strength gains. For example, it is conceivable that maximum strength training may increase the force/CSA ratio, suggesting that neural factors have played a major role in improved strength (Jones et al. 2008). Secondly, maximum strength training might facilitate selective hypertrophy of type IIx muscle fibers, compared to increases in all muscle fiber types during hypertrophic training (Campos et al. 2002). Hence, the force/CSA ratio may not always discriminate differences in adaptations between maximum strength (i.e. high load, low rep) and hypertrophic (i.e. medium load, high rep) training since this ratio might change due to training (Erskine et al. 2010). Isometric tests might identify these changes, because force-time curve have been shown to be affected by different contributions of neural and muscle-tendon properties (Folland et al. 2014). However, to target an increase in muscle mass, hypertrophic training may also improve strength-endurance properties (Campos et al. 2002, Walker et al. 2013) through enhanced metabolic functions e.g. increased acid buffering capacities, glycogen, ATP, creatine and phosphocreatine concentrations (Tallon et al. 2005, MacDougall et al. 1977). In addition, tests of muscular endurance, e.g. repetitions-to-failure or total workload (Mitchell et al. 2012), reflect the endurance properties of the muscle rather than the increase in muscle mass (Terzis et al. 2008, Walker et al. 2013). Therefore, changes in muscle hypertrophy cannot be monitored accurately by using performance tests. In regard to power training, there appears to be a good agreement with improved rapid force development and high velocity power generation (Cormie et al. 2010), which may provide justification for the use of these methods in monitoring.

Cross-sectional studies from the last decades have shown clear differences in isometric force-time curves between athletes with specific training backgrounds from different sports (Häkkinen & Keskinen 1989, Häkkinen & Myllylä 1990). Although maximal isometric contraction represents force production only over a narrow joint-angle range, rapid force production is dependent on time and this is a shared trait between isometric and dynamic contraction. This gives confidence that RFD has good external validity to dynamic performance based on partial generality (Hortobagyi et al. 1989). Changes in the initial part of the force-time curve are thought to represent neural adaptation during explosive-type strength-training (Häkkinen et al. 1985b, Aagaard et al. 2002) and musculotendinous stiffness affects both isometric and dynamic rate of force development (Wilson et al. 1994). Therefore, RFD is not only a product of neural activation but also contractile properties (Jewell and Wilkie 1958, Cavagna et al. 1981, Hannah & Folland 2014) and a relative contribution of these determinants changed during the phase of force-time curve (Folland et al. 2014). In addition, the late phase of the force-time curve is strongly associated to MVC (Andersen & Aagaard 2006). Consequently, it is not clear which one is the major contributor during the phase of the peak RFD (i.e. neural or contractile adaptation) and whether different training modes induce changes in peak RFD and time delay to reach this peak RFD.

Accordingly, it is reasonable to assume that systematic and frequently used isometric tests might identify some specific training adaptations during periodized maximum strength followed power strength training and hypertrophic training. Therefore, the aim of this study was to determine the possible bivariate correlations between individual and cohort changes in maximum isometric parameters (MVC, peak RFD and time to reach peak RFD) and individual neural and morphological adaptations during and after; 1) hypertrophic or 2) periodized maximal strength followed by power training. These training modes were chosen, since they are known to give different manifestations of long-term training adaptations and could, therefore, potentially reveal different monitoring needs. To determine a potential user-friendly isometric test for systematic training monitoring, we compared these selected isometric parameters to more sophisticated laboratory-based parameters typically used to determine neuromuscular adaptations in reference measurement time points.

Materials and methods

Subjects

Thirty-eight healthy men (28±6 years) were divided into two training groups (n=14+14) and one control group (C) (n=10). Subjects in the training groups were randomly selected to one of the two groups that performed either a 10-week maximum strength (MS) training period followed by a 10-week power (P) training period or 20 weeks of progressive hypertrophic (HYP) strength-training only (MS-P group: n = 14, age 30 ± 4 yr, height = 178 ± 4 cm, body mass 79 ± 4 kg; HYP group: n = 14, age 27 ± 5 yr, height = 177 ± 6 cm, body mass 71 ± 8 kg;

C group: n = 10, age 30 ± 4 yr, height = 180 ± 6 cm, body mass 84 ± 14 kg). None of the subjects had previously taken part in any systematic strength-training program, considered as more than once per week training frequency. Otherwise, all the subjects were physically active and took part in recreational physical activities for a few hours per week (endurance or ball games activity took place no more than 3 times per week). Subjects in the control group were instructed to maintain their normal living and physical activities during the corresponding intervention time between the pre- and post-measurements.

Each subject was carefully informed of all potential risks and discomforts and, thereafter, they singed an informed consent document. The study was conducted according to the declaration of Helsinki, and ethical approval was granted by the ethical committees of the University of Jyväskylä.

Experimental protocol

In the gym environment, the effectiveness of twice per week strength training was monitored using bilateral isometric leg press tests in a dynamometer at the beginning of every 7^{th} gym training session and also as a part of the laboratory tests performed before, after 10 and 20 weeks of strength training. These tests are referred to as "Monitoring tests" in the text. Other laboratory tests were taken to identify possible neuromuscular adaptations and changes in the performances, and are referred to as "Follow-up measurements".

Monitoring tests

Isometric maximum bilateral leg press tests (i.e. extension of the hip, knee and ankle joints) were performed in a seated position with 107° knee and 110° hip joint angles in a custom build dynamometer (University of Jyväskylä) and always after warm-up trials. Subjects were instructed to push "as fast and as hard as possible" and to maintain maximal force for 3 s or longer if maximal force level in these trials continued to increase. This was done with verbal encouragement. Trials were repeated three times (or more if performance was best in the third trial) and all contractions were real-time monitored to ensure no countermovement or pre-tension before contraction onset.

Follow-up measurements

Neuromuscular and performance tests, as well as body composition measurements were performed before, at 10 weeks and immediately after (20 weeks) the intervention. Seven days before the first measurement session all devices were set according to individual subject anthropometry. In addition, a familiarization session for the tests was performed. The performance measurements included several warm-up contractions, which were performed before the maximal isometric and dynamic tests.

The follow-up isometric measurements included maximal voluntary knee and leg extensions with similar instructions and amount of trials as during the monitoring tests. Knee extensions were performed unilaterally at 107° knee joint angle on the dynamometer chair (University of Jyväskylä). Maximal isometric bilateral leg press tests were performed using the same settings and the same dynamometer as in the gym-based monitoring tests.

The dynamic tests included maximum bilateral concentric leg extension (1RM) and single explosive repetitions using the 50% 1RM load, which were performed on a modified David 210 (David Health Solutions Ltd, Finland) horizontal leg press device including foot plate displacement and force sensors (University of Jyväskylä). The subjects were in a seated position (110° hip) and the movement started from 60±2° knee joint angle and ended with a fully extended leg (180° knee). The subjects performed 3-5 trials per test with a rest period of 2 min between trials. The trial with a highest force was selected for further analysis.

Surface Electromyography

In the follow-up measurements, electromyography (EMG) of vastus lateralis (VL) and vastus medialis (VM) muscles during knee extension was recorded (NeuroLog 824; Digitimer Ltd.) from the right leg using bipolar Ag/AgCl surface electrodes (10 mm pickup area and 20 mm inter-electrode distance, common mode rejection ratio >100 dB, input impedance >100 MΩ, baseline noise <1 μV rms). The electrodes were placed according to the SENIAM guidelines (Hermens et al., 1999) and these placements were tattooed subcutaneously with small ink dots before skin preparation (Häkkinen et al. 1985a). The tattoos ensured that electrodes were placed on the same location of the muscle during every measurement. EMG signals were sampled at a frequency of 2000 Hz, and pre-amplified at a gain of 500 (sampling bandwidth 10–500 Hz). Signals were passed real-time through an analog-to-digital (A/D) board converter (Power 1401) and recorded to a computer using Signal 2.16 software (Cambridge Electronic Design, Cambridge, United Kingdom). After measurements, EMG signal data was bandpass filtered (20–350 Hz) and transformed to root mean square (rms) EMG amplitude before being normalized to a corresponding EMGrms value measured during isometric MVC at each measurement session. Maximal EMG activity was analyzed from the plateau phase of isometric MVC over a 1000 millisecond time window. EMG activity during rapid force production was analyzed manually from the initial 100 and 500 milliseconds of isometric MVC. EMG activity of the VL and VM were combined and averaged during the analysis. Rectus femoris muscle activity was not measured because of the location of the muscle stimulation electrodes. Fast Fourier Transformation (Hamming, 1024 data points) was performed to obtain EMG median frequency (MF) over a 500 ms epoch. The average MF of the VL and the VM muscles were determined from the isometric MVC trials.

Muscle Stimulation

Four carbon film muscle stimulation electrodes (V-Trodes, Mettler Electronics Corp., Anaheim, CA, USA; diameter 70 mm) were placed on the mid and proximal portion of the right leg's quadriceps muscle belly. The stimulation electrode pairs were galvanically separated and skin under the electrodes was shaved and cleaned. Unilateral isometric knee extension torque responses to electrical stimulation in a resting muscle (resting stimulation) were determined at 107° knee joint angle on the dynamometer chair (University of Jyväskylä). The constant current was increased progressively in 20 mA steps between stimulations until a torque response plateau was observed. When maximal torque response was reached, 50% of the stimulation current was added. This supramaximal stimulus (150%) was used for all subsequent stimulations. The electrical stimulator (Digitimer Ltd., Model DS7AH, UK) delivered single rectangular pulses (1 millisecond, 400V). Resting stimulations were performed 2 times with 1 min between these twitches. Resting twitch force and its slope were analyzed from each twitch to determine the peripheral components (Bigland-Ritchie et al., 1978). In contrast, central drive was assessed by the interpolated twitch technique (Merton, 1954), including resting twitches before and 2 seconds after MVC and one twitch was delivered over the plateau phase of MVC. The subjects were able to reach MVC within 5 s and they were instructed to avoid brief torque peaks when they increased torque progressively towards the maximum. The level of voluntary activation was measured and calculated according to the formula by Bellemare & Bigland-Ritchie (1984):

$$\text{Activation level (\%)} = [1 - (T_{SIT} / T_{RT})] \times 100,$$

where T_{SIT} is the difference between the voluntary torque and twitch torque from the superimposed twitch, and T_{RT} is the resting twitch torque after MVC. EMG of biceps femoris muscle indicated that the above mentioned procedure did not stimulate this antagonist muscle.

Force and Angle

During the isometric leg press and knee extension trials, the plateau phase of isometric MVC was used to determine mean maximal force production with a 1000 milliseconds time window. The rate of force development (RFD) during the greatest 10 ms time window and time to reach this peak RFD from the onset of force were analyzed automatically from the fastest MVC trial during that particular measurement session by a custom-made script for Signal software (version 4.04, Cambridge Electronic Design, UK) and analyses were performed manually. Both isometric and dynamic measurement devices were equipped with in-built force sensors and, additionally, the dynamic device included angle sensors allowing evaluation of concentric actions. Force and angle signals were sampled at 2000 Hz, and signals were low-pass filtered (force 20 Hz and angle 75 Hz) using Signal software. Based on these parameters, mean angular velocity and mean power values during single concentric repetitions were analyzed separately for each of the six 20° windows, from 60° to full leg extension (180°). Mean power was calculated as the mean angular velocity multiplied by the mean torque for each sector separately. The explosive 50% 1RM load was calculated from the pre-measurement-determined 1RM load in all follow-up measurements.

Muscle cross-section area

Cross-sectional area (CSA) of the VL -muscle was determined by B-mode axial-plane ultrasound device (SSD-α10 model, Aloka Co Ltd, Tokyo, Japan). The 10 MHz linear-array probe (60 mm width), with extended-field-of-view settings, was manually moved slowly and continuously across the sagittal plane from lateral to medial diaphysis of the right thigh, avoiding any compression of the muscle tissue. Landmarks for determination were the midpoint between the greater trochanter and joint space on the lateral side of knee. This 50% of the femur length was marked subcutaneously with tattoo ink to ensure that the measurements were comparable throughout the study. CSA images were obtained throughout the probe movement, when the probe was moved manually slowly and continuously along a marked line on the skin. These images were combined into a panorama-view via in-built software, automatically. Three panoramic CSA images were taken and CSAs were measured by manually tracing along the outlines of the VL muscles of the images using Image-J software (version 1.37, National Institute of Health, USA). The mean of the two closest CSAs were averaged and taken as quadriceps CSA. One well-experienced tester performed all the measurements, and all images were analyzed by the same investigator. The validity and reliability of this method to determine CSA has been reported (Ahtiainen et al. 2010, Noorkoiv et al. 2010)

Strength-training Programs

The study design included two training groups (HYP and MS-P). Training of both groups was performed twice per week and every training session included a combination of 8-9 exercises in all major muscle groups. Bilateral leg press, knee extension and knee flexion exercises were performed in every training session and before the other exercises, such as bench press, shoulder press, seated row, lateral pulldown, triceps pushdown, biceps curl, back raises and abdominal crunches. Educated students in Biology of Physical Activity supervised and guided correct performance techniques for all subjects and exercises during all training sessions.

The HYP training mode was split into two identical and progressive 10-week periods (HYP I and HYP II), where the relative intensity remained the same, but the absolute loads increased individually due to the subject's improvement. The MS training was also based on progression, which was related to subjects' improvement in 1RM. In addition, periodization of the MS-P training program, in which maximum strength training was followed by power training and included mesocycle level progression. The MS and P training programs included leg press, knee extension, bench press, and shoulder press exercises. Other exercises were performed similarly as in the HYP program with regard to set and repetition number, as well as inter-set rest periods. During the P period, subjects performed one maximum strength session every three weeks in order to maintain their maximum strength levels. (Table 1)

Statistical Analyses

All data are reported as mean and standard deviation (SD). The Shapiro-Wilk test was used to determine normal distribution of the collected data. Differences for all dependent variables were assessed by ANOVA with repeated measures (Training variables = group × time), using Bonferroni adjustments as post hoc tests. Independent t-tests were assessed for group differences in different parameters. Pearson's product moment correlations assessed bivariate relationships between different dependent parameters. Significance level was defined as 0.05.

Reliability values (intra-class correlation coefficient and CV%) for all the measurements used were at acceptable levels: for isometric force 0.981 and 3.4%, for EMGrms 0.918 and 7.2%, for EMG median frequency 0.957 and 6.8%, for maximum twitch torque 0.994 and 1.3% and for calculated voluntary activation 0.732 and 1.9%, respectively. Statistical analysis was completed using IBM SPSS software version 24.

Results

Follow-up measurements in the laboratory. Bilateral concentric leg press force (1RM) increased in both HYP I (8±6%, P<0.001) and MS (11±6%, P<0.001) (Fig. 1e) after the first 10 weeks of training, but after HYP II only a slight improvement (3±4%) in 1RM took place that was not statistically significance. P training maintained (1±4%, P=n.s.) 1RM during the second 10-week period (Fig. 1e). EMGrms increased significantly (25±30%, P<0.05) during 1RM contraction only after 10 weeks of MS training (Fig. 1d).

During explosive repetitions with the 50% 1RM load, initial velocity and, thus, power increased (11±15%, P<0.05) concomitantly with EMGrms (22±26%, P<0.05) only during P (Fig. 1a, c). This was also observed in peak velocity and power (15±18%, P<0.05) and EMGrms (93±105%, P<0.05) at larger knee-joint angles (Fig. 1b, c).

The cross-sectional area of VL increased in both training modes during the first 10 weeks (HYP I 16±13%, P<0.001; MS 7±10%, P<0.01), but the following 10-week hypertrophic training (HYP II -1±6%, P=n.s.) and power training (P -3±5%, P=n.s.) periods only maintained CSA. The increase in CSA over the first 10-week training period correlated negatively with the increase in EMGrms over initial 500ms during isometric knee extensions (r=-0.63, P<0.05) after HYP I. Moreover, the changes in CSA and AL correlated negatively (r=-0.84, P<0.001) over the 20-week of hypertrophic training period (HYP I + II) (Fig. 2a).

Only the first 10-week training periods (MS and HYP I) increased knee extension MVC (13 ±11%, P<0.01; 11±12%, P<0.01). At the group level, AL during MVC changed significantly only after the P training period (-5±7%, P<0.05) (Table 2.). In addition, these changes in AL correlated positively with corresponding changes in knee extension MVC (r=0.65, P=0.059) and dynamic peak velocity (r=0.66, P=0.053) (Fig. 2c). Conversely, the increase in EMGrms over both the initial 100ms (39±45%), and 500ms (13±48%), were related (r=0.61*, P*=0.06; r=0.72*, P*<0.05, respectively) to the increase in MF (10±21%) during isometric knee extension MVC after the P period. The resting twitch peak force and the slope did not change significantly during any training periods in the group level.

Monitoring tests. Bilateral isometric leg press RFD over the steepest 10ms of the force-time curve increased (44±53%, *P*<0.05 and 47±73%, *P*<0.05) similarly during the first 7 weeks in both HYP I and MS training but, thereafter, RFD continued to increase (65±61%, *P*<0.01 vs. baseline) only during P training (Fig. 3). Time to reach peak RFD did not differ between groups in the beginning of the study, but at week 4 to 20 times differed significantly between groups (HYP I-II 41±18ms, MS-P 32±12ms; *P*<0.01, Fig. 4). The changes in RFD paralleled the changes in leg press MVC peak force during HYP training (HYP I, r=0.45; HYP II, r=0.59), but not during MS or P training. MVC peak force increased during the first 10 weeks in both training groups (HYP I 19±20% *P*<0.01; MS 8±12% *P*<0.05) (Fig. 3). In addition, MVC peak force was maintained between 10 to 20 weeks in the HYP training group. MVC correlated (r = 0.72, *P*<0.05) with changes in the 1RM loads after HYP II, when 1RM was only maintained and MVC even decreased (-9±4% *P*<0.001) during P training (Fig. 2d). Bivariate correlations between monitored isometric parameters and main training-specific parameters were presented in the Table 3.

Discussion

The results of the present study design show that isometric monitoring can be considered valid and effective in assessing strength-training adaptations. The present study showed that training-induced adaptations in maximum strength during the initial MS (0-10 week) period was accompanied by increased EMG and CSA, while the strength gain during the HYP I (0-10 week) period was accompanied by increased CSA only. MS followed by P training, during weeks 11-20, improved rapid force and velocity generations, as well as power production with concomitant increase in EMG during power performance (50% 1RM). The HYP II (11-20 week) period only maintained the gains in CSA and strength. The present results displayed specificity of different strength training modes as has been shown by several previous studies (Häkkinen et al. 1985a,b, Newton et al. 2006).

The changes in both the highest (MVC) and steepest phase (RFD) of isometric force-time curve paralleled the changes of dynamic performances (i.e. 1RM and explosive repetitions, respectively) during HYP and MS-P periods. This is likely due to specific aspects of each training mode, as well as neuromuscular adaptations behind them, influencing both isometric and dynamic test performance. Isometric leg press MVC (8±12% and 19±20%) improved only during both MS and HYP I periods with concomitant increases in dynamic leg press 1RM (11±6% and 8±6%), without significant correlation between these variables. However, only the hypertrophic training mode continued throughout the whole 20 weeks, which might decrease inter-individual differences in the HYP training group and, maybe therefore, the MVC and 1RM correlation was significant only between 10 to 20 weeks during hypertrophic training (HYP II). Supporting this possibility, similar strong correlations have been observed also in numerous other studies with experienced strength trainees (e.g. Haff et al. 1997 Kawamori et al. 2006),

Training mode-specific differences in the slope of the (bivariate correlation) trendlines between MVC and CSA (Fig. 2b.) showed that MVC reflected both peripheral and central adaptations. The different slopes of the trendlines suggest that the overall contribution of peripheral factors to improved MVC differed between HYP and MS-P. HYP showed a less steep slope and perhaps a greater reliance on increased muscle mass to produce greater force compared to MS-P. Therefore, the present correlation cannot specify precisely how much the change in isometric MVC could be explained by the increase of muscle size or other factors, alone. The subjects in the present study were untrained, which led to hypertrophy during both MS and HYP I periods (7±10% and 16±13%), as was the case e.g. in the study of Campos et al. (2002). However, the negative correlations between the changes in CSA and AL ($r=-0.84$, $P<0.01$; Fig. 2a) or EMG ($r=-0.63$, $P<0.05$) possibly reflects ineffective force production (Fig. 2b) relative to muscle size in the hypertrophic training, whereas MVC and AL correlated positively during the P period with increased EMG during MVC trials. In addition, the possible training-induced differences in the ratio of fast and slow twitch muscle fibers cannot be overlooked, because it may affect to MVC-CSA ratio (Young 1984), but also RFD during the initial phase of force-time curve (Häkkinen et al. 1985b).

One novel aspect of the present study was to determine the changes in time to reach peak RFD. Folland et al. (2014) observed that neural components were determinants that are more important in the initial phase of explosive force development, whereas contractile properties and particularly MVC may have more relevance in later phases of explosive force production. In support of this, MVC and RFD behaved similarly (Fig. 3) during the whole hypertrophic training (HYP I+II), but not during the maximum strength or power training periods. Concurrently, the time to reach peak RFD increased during hypertrophic training compared to other training modes. Penailillo et al. (2014) reported that decreases in the later phase of RFD might indicate training-induced muscle damage, which is one possible stimulus to generate a hypertrophic response (Schoenfeld 2010). The present results suggest that changes in peripheral structures/properties could improve isometric RFD to a certain level, but further increases seem to require an enhancement in the initial muscle activation (P; EMGrms 0-100ms 37.7±45% and 0-500ms 13±48%, 11-20wk). In addition, increased MF of EMG signals, which was observed in parallel (10.4±21%) might also be a sign of improved activation strategies (Un et al. 2013) via power training (P). The time to reach peak RFD shortened (~20%) after the beginning of maximum strength and power training modes, which could be a consequence of greater initial neural adaptation from the new stimuli (Moritani and Devries 1979, Narici et al. 1989) compared to pure contractile adaptations. It is well known that repeated dynamic maximum strength and power training contractions (Fig. 1c and 1d) enhance neural drive and, thus, muscle activation. In addition, their effect can also be observed in isometric contractions and, thus improved peak RFD and time to reach it. Tillin et al. (2012) showed that isometric and dynamic concentric explosive force production behaved similarly until 75ms from the force onset and peak RFD were produced during that time span in the present study. The positive bivariate correlation between the changes of AL in isometric condition and peak leg press velocity during explosive contractions also reinforces this speculation. This finding is in-line with a study of de Ruiter et al (2004), who showed a strong correlation between AL and initial EMG amplitude during fast knee extensions. Also, Del Balso & Cafarelli (2007) showed a strong correlation between RFD and the rate of muscle activity due to progressive isometric training. Enhanced muscle activity in the present study could, at least partly, be explained by the concomitant increase in MF; possibly due to greater use of fast twitch muscle fibers and conformed recruitment control strategies for maximal explosive force onset (Gerdle et al. 1988, Solomonow et al. 1990). Otherwise, the enhancement of muscle activity and corresponding 1RM after MS training were not associated with the changes in MF. This might be due to more synchronous motor unit firing of muscle fibers and/or the changes in muscle architecture, resulting from the increase in the cross-sectional area. In addition, the adaptations in the complex architectures of muscle and tendon-aponeurosis might explain early improvements of monitored RFD without concomitant neural changes (Bojsen-Moller et al. 2005, Earp et al. 2011). Unfortunately, specific changes in tendon-aponeurosis, pennation angles or fascicle lengths of different muscles were not measured in this study. Nevertheless, the present study measured the CSA of VL muscle, which reflects a combination of changes in pennation angles and fascicle length.

From a training monitoring point of view, based on RFD, it could be that the high intensity P period continued too intensively and/or was too monotonous for optimal performance gains. Typically, power-specific training periods last only for 2-6 weeks (Fleck & Kraemer 1987). Single maximum strength-training sessions between power training most likely did not offer an adequate alternative stimulus to progress improvement in monitored RFD or maintain AL, although these were able to maintain CSA and dynamic maximum strength levels. Nevertheless, Häkkinen et al. (2003) have shown that RFD could increase parallel to MVC and 1RM also after 14 weeks of training, if the volume of maximum strength training is of greater proportion of power training than in the present study. However, the study from Häkkinen et al (2003) used a longer time-window in their RFD analysis, which might explain a stronger association with maximum strength (Andersen & Aagaard 2006). Shorter RFD windows may have better functional validity in sport performances (Abernethy et al. 1995), but marginally reduces reliability (Wilson et al. 1993). From the periodization perspective, intensive strength-training where power is combined with maximum strength can also, in some trainees, lead to a training plateau or even to a state of overreaching and/or early phases of overtraining. In the present study, the decreased RFD and a descending trend of evoked resting twitch force response support this suggestion. Fry et al. (1994 a,b) observed that training-specific properties were impaired even though e.g. maximum strength levels were still maintained, when approaching the state of overtraining. In addition, a descending trend was also observed in AL in the power training group, however the changes in the AL correlated positively with their ability to produce peak leg press velocity during explosive contractions, even though velocity production decreased in some individuals (Fig. 2c; subjects A, B and D) during the present study. Therefore, some potential for overreaching of the central nervous system could be suggested by this data (Kreider 1998), despite the fact that reliable diagnostic tests for overreaching do not exist (Kraemer & Nindl 1998, Coutts et al. 2006). The importance of training monitoring comes from individual needs to optimize training; an ideal training program for some may undertrain or overtrain others. RFD has been earlier shown to be associated with adaptations in the nervous system (Miller et al.

1993). The present study confirmed the findings by Miller et al. (1993) in the actual strength-training, but also showed the importance of effective use of peripheral factors behind the monitored RFD parameters. At the same time, potential individually undulating overreaching periods and differences between intra-group levels in subject's physiological capacity and performances were able to be detected using the presented isometric parameters in strength-training monitoring.

CONCLUSIONS

Different phases of isometric force-time curve were influenced by both central and peripheral properties to varying degrees, but also reflected the specificity of the prevalent training mode. The changes in peak RFD and time to reach peak RFD were, in several ways, associated with neural enhancements due to maximum strength and power training, when contractile properties had more relevance in the changes of these parameters due to hypertrophic training. The fact that there was a between-group difference in the time to reach peak RFD gives confidence that the changes in isometric RFD reflect the development of explosive force production, and that this could be a useful monitoring tool representing (predominantly) neural adaptation. Conversely, MVC and dynamic 1RM were only related after continued hypertrophic training and more likely represent peripheral properties/adaptation. Therefore, systematic monitoring of RFD brings valuable information about an ambitious trainees' current condition and responses to recent training stimuli.

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Conflict of interest All authors declare no conflicts of interest.

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ABBREVIATIONS

1RM	One repetition maximum
AL	Activation level
ATP	Adenosine triphosphate
CT	Computered tomography
CSA	Cross-sectional area
CV%	Coefficient of variation
EMG	Electromyography
HYP	Hypertrophic
MF	Median frequency
MS	Maximum strength
MVC	Maximum voluntary contraction
P	Power strength
RFD	Rate of force development
rms	Root mean square
SD	Standard deviation
VL	Vastus lateralis muscle
VM	Vastus medialis muscle

TABLE LEGENDS

Table 1. Training programs.

Table 2. Absolute values of activation level, resting twitch force, resting twitch slope and median frequency before and after each training period or control period.

Table 3. Correlations between monitored isometric parameters and main training-specific parameters

Table 1. Training programs

		Sets	Repetitions	Load	Rest			Sets	Repetitions	Load	Rest
	1-4wk	2-3	12-14	60% 1RM	1 min		11-13wk	2-3	12-14	60% 1RM	1 min
HYP I	5-7wk	2-3	10-12	70% 1RM	2 min	HYP II	14-16wk	2-3	10-12	70% 1RM	2 min
	8-10wk	3-4	8-10	80% 1RM	2 min		17-20wk	3-4	8-10	80% 1RM	2 min
	1-4wk	2-3	6-10	70-75% 1RM	3 min		11-13wk	3	4-10	30-70% 1RM	3 min
MS	5-7wk	3-4	4-10	70-85% 1RM	3 min	P	14-16wk	4	4-8	30-50% 1RM	3 min
	8-10wk	2-6	3-9	80-90% 1RM	3 min		17-20wk	5	6-8	30-50% 1RM	3 min
						Sessions to maintain max strength levels during the power period					
							At 11wk/1st	3	4-6	87,5% 1RM	3 min
							At 14wk/1st	3	3-5	90% 1RM	3 min
							At 17wk/1st	3	2-4	92,5% 1RM	3 min

Note: MS and P training programs included leg press, knee extension, bench press and shoulder press exercises and other exercises the same as with HYP program.

Table 2. Absolute values of activation level, resting twitch force, resting twitch slope and median frequency before and after each training period or control period

Subject group		Activation level [%]				Resting twitch force [N]			Resting twitch slope [N/s]			Median frequency [Hz]			
		Pre	Mid		Post	Pre	Mid	Post	Pre	Mid	Post	Pre	Mid		Post
MS-P	Mean	90.9	91.0	‡	85.6	50.2	51.1	45.5	903.5	904.3	810.3	66.4	64.5	‡	69.5
	Sd	6.1	4.7		8.1	16.6	23.6	12.4	320.0	374.7	127.9	11.3	9.7		9.2
HYP	Mean	90.7	89.0		89.9	55.8	49.9	55.9	880.8	902.3	887.1	66.0	65.8		64.2
	Sd	3.1	7.7		7.1	15.2	11.6	13.0	227.2	197.8	169.3	12.3	12.0		9.7
Control	Mean	89.7			89.6	48.2		46.6	937.6		896.2	68.5			67.6
	Sd	7.3			6.3	7.4		20.1	145.3		243.9	13.3			10.1

‡ $P < 0.05$, Significant differences between mid and post measurements (P training)

Table 3. Correlations between monitored isometric parameters and main training-specific parameters

			Acceleration (0-20° knee joint angle)	Peak Velocity	1 RM	CSA
MVC	**MS-P**	Pre-Mid			r=-0.543 p=0.068	
		Mid-Post				
		Pre-Post			r=-0.611 p=0.046	
RFD	**MS-P**	Pre-Mid				r=0.571 p=0.041
		Mid-Post				
		Pre-Post				r=0.783 p=0.004
MVC	**HYP**	Pre-Mid				
		Mid-Post	r=0.584 p=0.059		r=0.759 p=0.007	
		Pre-Post			r=0.561 p=0.058	
TimeRFD	**HYP**	Pre-Mid				
		Mid-Post				
		Pre-Post	r=0.694 p=0.018			

FIGURE CAPTIONS

Fig. 1. The changes after MS and P training in a) acceleration b) angle-velocity curve c) EMG during explosive repetitions d) EMG during 1 RM repetitions and e) 1 RM load (P<0.05; *** P<0.001)*

Fig. 2 The correlations between relative changes of
a) activation level and cross sectional area (CSA) after 20 week HYP I+II training,
b) isometric knee extension MVC and CSA after 20 week MS+P and HYP I+II training,
c) activation level and leg press peak velocity at 50% 1RM after P training period,
d) isometric leg press MVC and dynamic leg extension 1RM after HYP II training period.

The numbers 1-13 represent individual subjects in the HYP group and the letters A-K subjects in the MS-P group. The subjects J and K refused to participate measurements with electrical stimulation and the part of data from post measurements were not collected (subjects 7, 11 and 13).

*Fig. 3. The relative changes in isometric leg press RFD and MVC peak force compared to before training values (RFD, *P<0.05; MVC, ##P<0.01).*

Fig. 4. The time to reach peak RFD in isometric leg press.

Fig. 1

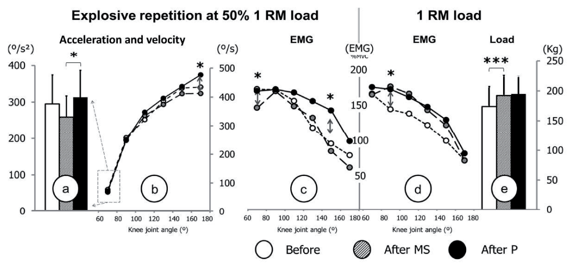

Fig. 1. The changes after MS and P training in a) acceleration (60-80° knee joint angle) b) angle-velocity curve c) EMG during explosive repetitions at 50% 1 RM load d) EMG during 1 RM repetitions and e) 1 RM load (* P<0.05; *** P<0.001)

254x190mm (300 x 300 DPI)

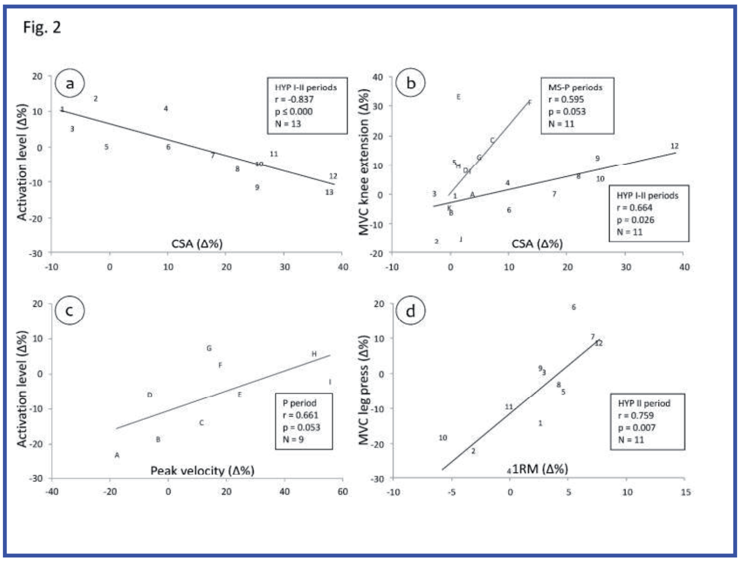

Fig. 2 The correlations between relative changes of a) activation level and cross sectional area (CSA) after 20 week HYP I+II training, b) isometric knee extension MVC and CSA after 20 week MS+P and HYP I+II training, c) activation level and leg press peak velocity at 50% 1RM after P training period, d) isometric leg press MVC and dynamic leg extension 1RM after HYP II training period. The numbers 1-13 represent individual subjects in the HYP group and the letters A-K subjects in the MS-P group. The subjects J and K refused to participate measurements with electrical stimulation and the part of data from post measurements were not collected (subjects 7, 11 and 13).

423x317mm (300 x 300 DPI)

Fig. 3

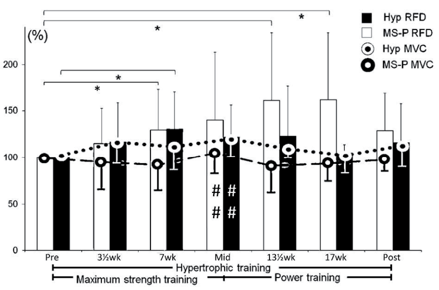

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Fig. 4

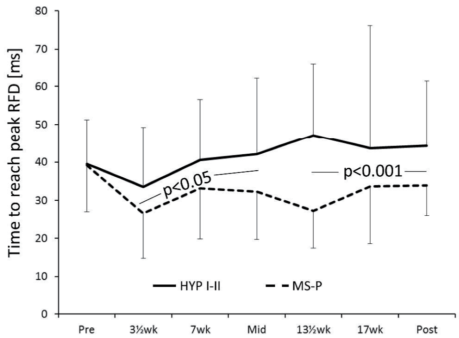

Fig. 4. The time to reach peak RFD in isometric leg press.

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IV

INCREASED RATE OF FORCE DEVELOPMENT DURING PERIODIZED MAXIMUM STRENGTH AND POWER TRAINING IS HIGHLY INDIVIDUAL

by

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Increased rate of force development during periodized maximum strength and power training is highly individual

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Abstract

Maximum strength training induces various improvements in the rate of force development on a group-level, but no study has investigated inter-individual adaptations in RFD. Fourteen men (28±6 year-old) performed the same 10-week maximum strength and then 10-week power training period. Maximal force and RFD were recorded during maximal isometric leg extension voluntary contractions repeatedly before every 7th training session (2 sessions/week). After the intervention, subjects were retrospectively divided into three groups based on their RFD-improvements: 1) improved only during the maximum strength period (MS-responders, +100±35%), 2) improved only during the power period (P-responders, +53±27%) or 3) no improvement at all (Non-responders, +3±9%).

All groups increased dynamic 1-RM equally, but baseline 1-RM was greater ($p<0.05$) in Responder vs. Non-responder groups. MS-responders had higher stimulation-induced torque at baseline and they improved (+35±28%) power production at 50%1RM load more than P- (-7±20%, $p=0.052$) and Non-responders (+3±6%, $p=0.066$) during the maximum strength training period. MS-responders increased vastus lateralis cross-sectional area (+12±9%, $p<0.01$) as did P-responders (+10±7%, $p=0.07$), whereas Non-responders did not.

Free androgen index (FAI) in Responders was higher (+34%, $p<0.05$) compared to Non-responders at baseline. The maximum strength period decreased testosterone (-17±12%; 17±22%), FAI-ratio (-12±14%; -21±23%) and testosterone/cortisol-ratio (-17±25%; -31±20%) in MS- and P-responders, respectively. During the P-period hormonal levels plateaued.

Periodized strength training induced different inter-individual physiological responses and, thus RFD development may vary between individuals. Therefore, RFD seems to be a useful tool for planning and monitoring strength training programs for individual neuromuscular performance needs.

Keywords: strength training, individual response, training monitoring, RFD, MVC

Introduction

Rapid force production is critical for sport performance and important for normal muscular function. When it is impaired, muscular function is compromised in individuals of various populations; e.g. elderly, patients, or it separates the medalists from non-successful athletes. Interestingly, rapid force production ability seems to be more sensitive to determine acute and chronic changes in the neuromuscular system compared to maximal voluntary contraction force (e.g., Angelozzi et al. 2012; Crameri et al. 2007; Jenkins et al. 2014; Penailillo et al. 2015). This is one of the reasons why, the rate of force development (RFD) has recently become quite popular for characterizing changes in different physiological mechanisms due to strength training programs (Maffiuletti et al. 2016).

It is well known, that identical strength training programs may cause alternating responses between individuals and, it has been demonstrated that one-repetition maximum (1-RM) and cross-sectional area (CSA) increases may differ or even not increase at all in some individuals undergoing training (Ahtiainen et al. 2016). Possibly, these different responses to training may be due to the trainees' genetic make-up and/or exercise training background. Recent speculations suggest that individual training responses can also vary between different (specific) aspects of neuromuscular performance and muscle morphology, thus, training may still improve an outcome variable other than the main measure (Churchward-Venne et al. 2015). From another perspective, different training stimuli could evoke similar chronic training responses between individuals. Trainees' individual physical qualities may benefit more from some specific stimulus at a particular moment (in time) depending on his/her previous training adaptations, using such principles of the periodization continuum.

It is possible the benefits of current training stimuli might be observable through acute training session responses at specific points in the training period for targeted exercises. Physical readiness to respond to training and the evoked stimulus by exercise might be feasible to evaluate based on exercise-induced fatigue. Previous studies have shown that stronger athletes (Ahtiainen & Häkkinen, 2009) could obtain greater maximal strength fatigue levels, and power athletes (Häkkinen & Myllylä, 1990) could obtain greater fatigue levels in fast force production compared to their endurance-trained counterparts. In addition, some physiological indicators reflect acute (e.g. metabolic / lactate) and chronic (e.g. endocrine / basal testosterone and cortisol) adaptations in performance capacity due to long-term, progressive strength training (Busso et al. 1990, Fry et al.1994). In other words, the same strength training program may optimally stress some of the trainees, but other trainees could be under- or over-trained.

With the above points in mind, the aim of the present study was to investigate individual variation in the improvement of RFD and identify underlying adaptations during both a maximum strength training and a subsequent power training period. Both of these training modes have been shown to enhance RFD at a group level but each program creates different dynamic training stimuli in which (potentially) some individuals respond and some do not. We hypothesized that physiological differences and individual acute responses after identical exercises in different individuals will help to explain divergences between Responders and Non-responders to these training programs.

Methods

All subjects received written and verbal descriptions of the study. All risks and benefits were explained to participants and written informed consent was obtained. The University Ethics Committee gave approval for all experimental procedures in the study, which was conducted according to the Declaration of Helsinki.

Subjects

Fourteen healthy physically active male subjects (age 28±5 years; height 179±5 cm; BMI 25±4), but with no regular background in strength training volunteered to participate in this study. The subjects were not allowed to train with endurance exercises more than two times per week during the study. The subjects were instructed to follow the Finnish national nutrition recommendations and avoid smoking.

Strength Training

All subjects completed a progressive strength training program for 20 weeks including exercises for all body parts, however, leg exercises (leg press, knee extension and flexion) were performed in every training session in the gym twice per week. All leg exercises were performed always before the other exercises. The strength-training program was periodized to a 10-week maximum strength training period followed by a 10-week power strength-training period (with separate maximum strength sessions maintained every fourth session). The overall volume of training loads decreased from the maximal strength period to the power strength period, while the concentric velocity of repetitions was high. Training volume decreased in the final sessions before the laboratory measurements at the end of both training periods, in the form of pre-testing tapering. All subjects followed the same training program under direct supervision and their relative loads were equal.

Training Monitoring

After warm-up, all subjects performed isometric voluntary bilateral leg extension (Fig 1) contractions with maximal effort at the beginning of every 7^{th} training session in the gym, matching the laboratory measurement methods. Maximum RFD over the steepest 10 ms and peak force (MVC) were analyzed from the recorded force-time curves at 107° knee joint angle in the isometric leg extension device (University of Jyväskylä, Finland). At least two isometric trials were performed and if the final trial improved more than 5% from the previous trial then the subject was asked to perform one more trial. The highest values from each monitored session were used in analyses. This was used as a basis to categorize each individual into maximum strength (MS) or power strength (P) responders (based on the timing of their RFD improvements during the intervention) or into the Non-responder group.

During these monitored training sessions, the subjects always performed the allocated leg press exercise (M16, David Health Solution Ltd, Finland) before the other exercises. The isometric leg extension test was also repeated after the last leg press set to determine loading-induced fatigue based on changes in RFD and MVC parameters. In addition, volume load (load [kg] ×

repetitions) of the leg press was calculated, as well as fingertip blood samples were collected before and after the exercise to determine blood lactate concentration (see Biochemistry Measurements).

Laboratory Measurements

Neuromuscular, hematological and performance characteristics were measured in the laboratory before and after 10 and 20 weeks of training. All laboratory measurements were performed following 48 hours of rest and at the same time of day (±1 hour) for each time point.

Performance Measurements

The isometric leg extensions were performed in the beginning of the laboratory measurements and matching the tests performed in the gym. Dynamic 1RM and power at the load of 50% 1RM repetitions were determined by a leg press device (D210, David Health Solution, Finland) that has been modified to include distance and force sensors. The range of movement began at a knee angle of 60° and 110° hip angle and continued until the legs were fully extended (full extension = 180°) with a belt fixed at the hip. The subjects performed at least two (but no more than 5) trials with the load increased after each successful repetition. In addition, in the power tests, the subjects performed at least two trials and if the final power value was more than 5% higher than the previous trial, an additional repetition was performed. The subjects were encouraged to push as fast and hard as possible with correct performance technique during all trials.

In the performance measurements, dynamic (leg press) and isometric force (leg extension), as well as torque (knee extension with electrical stimulation) were sampled at 2000 Hz and raw data were low-pass filtered at 20 Hz offline. Displacement data during dynamic leg press trials were low-pass filtered at 75 Hz.

Stimulation Procedure

Unilateral isometric knee extensions at 107° knee joint angle were used to assess voluntary activation level (AL) via the interpolated twitch technique (ITT) on an isometric chair (University of Jyväskylä). Four, galvanically paired, self-adhesive muscle stimulation electrodes (6.98 cm V-trodes, Mettler Electronics Corp, USA) were positioned on the proximal and middle regions of the quadriceps muscle belly and surface electromyography signals were collected from vastus lateralis (VL) and medialis (VM). The stimulation protocol included increasing constant-current single 1 ms rectangular pulses (Model DS7AH, Digitimer Ltd, UK) until a torque plateau was observed. Based on this stimulation current, 25% was added to ensure supramaximal stimulus intensity. During the plateau of peak force in maximal voluntary isometric trials, the same supramaximal single-pulse stimulus was delivered and then one further pulse 2 s after cessation of contraction to the relaxed muscles for voluntary activation assessment. The stimulation protocol did not stimulate antagonist muscles based on EMG of biceps femoris (BF). The level of voluntary activation (VA) were calculated based on the formula of Bellemare and Bigland-Ritchie (1984); VA% = [1 – (superimposed twitch torque / passive twitch torque)] × 100.

Surface Electromyography (EMG)

Bipolar surface Ag/AgCl EMG electrodes (diameter 10 mm, inter-electrode distance 20 mm, common mode rejection ratio >100 dB, input impedance >100MΩ, baseline noise <1 μV rms; University of Jyväskylä, Finland) were placed on the VL, VM and BF of the right leg after shaving and skin abrasion according to SENIAM guidelines (Hermens et al. 1999). EMG signals were sampled at a 2000 Hz frequency and amplified at a 500 gain with 10-500 Hz bandwidth filtering. Signals were AD converted (Micro1401, Cambridge Electronic Design, UK) in real-time and recorded by Signal software (Version 4.04, Cambridge Electronic Design, UK). During the analysis, EMG signals during were band-pass (20-350 Hz) filtered and root mean square (rms) converted for EMG amplitude.

Muscle Cross-sectional Area

Cross-sectional area (CSA) of VL was assessed by extended-field-of-view ultrasound (B-mode, model SSD-α10, Aloka Co Ltd, Japan) with a linear array probe (10 MHz; 60 mm width), including the extended-field-of-view mode (Ahtiainen et al. 2010). The probe was oriented in the axial plane and moved slowly and continuously from the lateral to medial side of the right thigh along the skin via a marked line avoiding excessive compression of the muscle tissue. Three panoramic images of CSA were taken at 50% femur length from the lateral aspect of the distal diaphysis to the greater trochanter. The panoramic CSA images were composed by in-built software of the ultrasound device based on adjacent images throughout the movement. The border of VL was tracked manually using Image-J software (version 1.37, National Institute of Health, USA). The mean of the two closest CSA values was taken as the result.

Biochemistry Measurements

Venous blood samples (10 mL) for the determination of hormone concentrations in serum were obtained in the morning after 12 hours fast and analyzed by a qualified laboratory technician. Collected whole blood samples were centrifuged (Megafuge 1.0 R, Heraus, Germany) at 3500 rpm for 10-minute before serum was separated and stored at -80°C until analysis. Testosterone (T), cortisol (C), sex-hormone binding globulin (SHBG) analyses were performed using chemical luminescence techniques (Immulite 2000 XPi, Siemens, Llanberis, UK) with hormone-specific immunoassay kits (Siemens) (analytical sensitivity and assay precision values for T (0.5 nmol/l, 10.6%), C (5.5 nmol/l, 7.7%) and SHBG (0.2 nmol/l, 7.6%). Both T/C-ratio and free androgen index (FAI = 100×T/SHBG) were calculated based on these results. Concentration of free testosterone (FT) was derived from total T, SHBG and albumin concentration, calculated according to the Vermeulen formula (Vermeulen et al. 1999)

To determine blood lactate concentrations during training monitoring, capillary blood samples (20µL) were taken from the fingertip before and after the leg press exercise into a reaction tube containing an anticoagulant and a hemolyzing agent. These samples were analyzed using a lactate analyzer (Biosen, S-line Lab + EFK, Magdeburg, Germany).

Statistical Analyses

Mean and standard deviation (SD) are presented as descriptive statistics. Non-parametric tests were used for statistical analyses with SPSS software (version 24, IBM SPSS Statistics). Between-group comparisons were made by Mann-Whitney U tests and within-group comparisons with the Wilcoxon matched-pairs test. The level of significance was set at $p < 0.05$.

Results

The RFD over the steepest 10ms on the leg extension dynamometer was used to categorize sub-groups for Responders to maximum strength (MS, n=6) and to power (P, n=4) training or neither both, as Non-responders (Non, n=4).

Background anthropometrics differed between the Responders and Non-responders only in BMI, Non-responders showing lower value than MS- ($p=0.067$) and P-responders ($p<0.05$). Anthropometric values in sub-groups were; height 180±4 cm, BMI 25±3 for MS-, and 177±7, 29±4 for P-, and 178±7, 22±2 for Non-responders.

The RFD from the monitoring sessions (averaged over week 3½ to week 10) during the maximum strength training period increased by +100±35%, ($p<0.001$) in the MS-responders, P-responders increased only by +11±8% ($p<0.001$) and Non-responders showed decreases of -17±11% ($p<0.001$) in their RFD during this period. Following the power training period (week 13½ to week 20), RFD of P-responders increased by +53±27% ($p<0.001$) compared to their initial level, while MS-responders maintained their RFD improvements (+103±46%, $p<0.001$) and the Non-responders were unchanged (+3±9%; n.s) from their initial levels (Fig 2a,b). The changes between the groups differed significantly ($p<0.05$-0.001), except for the MS- and P-responders at the end of the study (n.s.). After MVC normalization, RFD in the MS- and P-responders improvements matched those without normalization, but in the Non-responder the RFD responses followed those of P-responders ($R^2 = 0.66$) (Fig 2c,d).

The initial level of leg press 1RM loads were significantly lower ($p<0.05$) in the Non-responders (149±21 kg) compared to the combined Responder groups (MS- 202±20 kg, P-responders 178±23 kg), but the differences in CSA of the VL muscle were not statistically significant before training (Non- 23±4cm², MS- 27±7cm², P-responders 29±5cm²). Relative changes in 1RM were similar between the groups throughout both training periods, but CSA significantly increased only in the Responders (MS- +12±9%, $p<0.01$; P-responders +10±7%, $p=0.07$) during the maximum strength training period, while Non-responders (+2±3%, n.s.) maintained their pre-training CSA. In addition, only MS-responders enhanced their EMG (+113±76%, $p<0.01$) even though their 1 RM was unchanged (-1±3%, n.s.) during the power training period, although both MS- (-5±4%, $p<0.05$) and P-responders (-5±3%, $p=0.07$) decreased CSA during the power period compared to their initial CSA values (Table 1).

During explosive leg press contractions at a 50% 1RM load from the beginning of the study, the MS-responders tended to improve mean (+24%, $p=0.076$) and peak (+35%, $p=0.09$) power during the maximum strength period and these differed from the changes of the other two groups in mean ($p<0.001$) and peak ($p=0.07$) power responses. The initial EMG of the P-responders decreased (-22±14%, $p=0.06$) during the maximum strength period, but then EMG increased (+57±10%, $p=0.077$) during power training (+35±18% from 0 to 20 weeks, $p<0.01$) at the first half of the movement during the power period. EMG amplitudes in MS- and Non-responders were not changed systematically during either training period.

In MS-responders, electrical stimulation-induced resting twitch force (+25% vs P-responders; +47% vs Non), twitch force/time –ratio (+18% vs P-responders; +45% vs Non) and twitch force/CSA –ratio (+30% vs P-responders; +26% vs Non) were higher compared to other groups before the study. Before the power period, AL in P-responders was higher (+5%, $p<0.05$) compared to Non-responders.

The baseline levels of SHBG (+34%, $p<0.05$) of Non-responders was higher and FAI –ratio (-34%, $p<0.05$) was depressed compared to Responders. Serum TT (MS -17±12%, P -17±22%; $p<0.05$) and FT (MS -11±10%, P -19±24%; $p<0.05$), as well as FAI (MS -12±14%, P -21±23%; $p<0.05$) and T/C –ratios (MS -17±25%, P -31±20%; $p<0.05$) were depressed in the Responder groups, but not in Non-responders during the maximum strength period only (Table 2).

The maximum strength leg press exercise (in the gym; averaged weeks 3½ and 7) induced greater acute decrements ($p=0.068$) in MVC of MS-responders (-29±9%) compared to the other groups (P -17±6%, Non -18±8%) during the maximum strength training period. In addition, at the same time the averaged RFD of MS-responders decreased (-31±6%), which differed almost significantly ($p=0.088$) compared to the other groups (P -19±13%, Non -23±11%). However, blood lactate levels in P-responders were elevated (+8.8±1.7 mmol/L) significantly more than in Non (+5.0±1.3 mmol/L, $p<0.05$) or MS (+5.5±1.8 mmol/L, $p=0.056$) responders (Fig 3.).

The power training leg press exercise (in the gym; averaged weeks 13½ and 17) induced significantly ($p<0.05$) greater acute decrements in MVC productions of Responders (MS -21±5%, P -20±8%) compared to Non-responders (-13±3%). No significant differences in RFD (MS -39±15%, P -39±17%, Non -30±14%) or blood lactate levels (MS 5.4±1.9 mmol/L, P

5.5±1.3 mmol/L, Non 4.8±1.5 mmol/L) were observed between the groups after leg press exercise during the power training period (Fig 3.).

Discussion

The present study highlighted highly individual improvements in the RFD, even though the strength training protocols were identical in all groups using the same relative training volumes. Changes in RFD have previously been shown to be closely related to several critical neuromuscular adaptations both peripherally and centrally (Häkkinen et al. 1985, Maffiuletti et al. 2016) and, thus, in the present study RFD was selected as a criterion to categorize sub-groups (i.e., Responders vs. Non-responders). This study design was novel, since previous "individual response" studies were based on maximum strength or muscle mass changes during strength training (Erskine et al. 2010, Ahtiainen et al. 2016). In this study, the periodized strength training program was created in an attempt to enhance both maximal strength and rapid force production, because these properties have been previously shown to affect RFD (Andersen et al. 2010). Moreover, it is well known that maximal strength and rapid force production are closely linked (Andersen and Aagaard 2010) and, thus, delivered altered/varying stimuli to the same training target.

The initial dynamic 1RM strength and CSA of VL were similar in both MS- and P-responders. It should be noted, however, that baseline maximal strength and muscle size were lower in Non-responders. This group also showed lower (p=0.019) free androgen index (FAI) compared to Responders. In all groups relative improvements in 1RM were similar throughout the maximum strength training period, although the changes in CSA were minimal in the Non-responders compared to MS- and P-responders. Interestingly, basal serum hormonal concentrations such as total testosterone, free testosterone, and testosterone/cortisol and FAI–ratios were depressed (p=0.01-0.03) during the maximum strength period in the Responders, but this was not observed in Non-responders. Following the power strength training period, all groups maintained 1RM and CSA levels. Muscle activation did not differ between the three groups systematically during 1RM trials. However, there were signs that neural deficit assessed by ITT, was greater (p=0.06) in Non-responders compared to Responders during isometric MVC in the beginning and after the first 10-week training period of the study. Moreover, the method to normalize RFD to this MVC might be questioned in the training study design, since during power type of strength training MVC might even decrease and, thus, RFD normalized in this fashion may lead to misinterpretations e.g. with plateaued RFD.

Initially, MS-responders showed the highest resting twitch (RT) force and RT force/time –ratio, compared to the other groups before the training intervention. Furthermore, RT force and RT force/time –ratio in P increased to the same level as MS throughout the maximum strength period, while Non-responders only maintained their levels. Interestingly, MS-responders had a higher (26 to 30%) RT force/CSA –ratio. Since MS did not differ in voluntary force production, but differed in involuntary force production, this may indicate that neural deficiencies were specific to initial activation and potentially gave these subjects a greater potential to improve power production compared to others. These findings possibly reflect part of the mechanisms behind previous observations that stronger individuals possess more favorable neuromuscular characteristics for superior improvements in maximal power production (Cormie et al. 2010, Cormie et al. 2011). MS-responders also improved their ability to effectively activate increased muscle tissue during dynamic explosive contraction as was shown by the increased mean ($p=0.03$) and peak ($p=0.07$) power after the maximum strength period compared to other the groups.

At the pre-, mid- and post-measurements in the present study, power determination was performed using 50% 1RM from the pre-training loads. Due to the enhanced 1RM during the mid- and post-measurements, these relatively lower loads, possibly required the subjects to improve power via higher contraction velocities. Therefore, it may be assumed that MS-responders possess a better peripheral 'readiness' to train, which might partly explain their enhanced power productions. This suggestion is in-line with the findings of Baker (2001) who concluded that higher power production requires adequate strength levels before velocity-specific power improvements could be established. Due to this consideration, the present study design was built to follow this linear periodization continuum from maximum strength to power training.

The present study was also novel by investigating separate training sessions during the overall training program and using differences between the acute responses to identify mechanisms for individual adaptations. Greater training volume loads due to higher absolute training loads used in the gym, might create stronger stimuli for peripheral adaptations (e.g. CSA, RT parameters) to reflect alternative demands of the training modes between the Non-responder versus the MS and P responder groups. Although the overall training program and volume were the same in MS- and P-responders during the maximum strength training period, physiological stress induced by training may have been optimal for some subjects, while the stimulus may have been either too intense or not sufficiently intense for others, e.g. depending on the training background and/or genetics of the individual. The blood lactate values observed in P after the maximum strength exercises in leg press indicated a greater metabolic stress, where the anaerobic glycolytic system was challenged. In some cases, this continued high exertion level might lead to possible states of overreaching or even early level overtraining, which might explain the observed decreasing trend in anabolic hormone levels and testosterone/cortisol and FAI -ratios parallel with a maladapted RFD. It has been suggested that hormonal regulations may be one important factor for trainability (Häkkinen et al. 1985, Kraemer et al. 1990). Therefore, delayed RFD improvement of the P-responders compared to MS responders might be a consequence of their greater training-induced fatigue during every maximum strength training session. In other words, it is possible that maximum strength training induces such a high level of fatigue in these individuals that potential increases in performance are suppressed during the monitoring tests. This premise is support by the work of Hackney et al. who proposed neuroendocrine dysregulation, in particular anabolic hormone suppression, may compromise select exercise training adaptation (Hackney & Lane 2015, Hackney 2006). Thus, power training offered a different training stimuli with a marked reduction in volume load (decreased to 60%), which might be more suitable for the individuals in the P group to realize training-induced RFD adaptations.

One unique finding was the sign of the neural depression in P-responders with above-mentioned anabolic hormonal stagnation. This was observed in their muscular activity at the first 20 degrees joint angles in the power determination tests which dropped (-22±14%, $p=0.06$) after the maximum strength period and recovered (57±10%, $p=0.077$) during the power strength training period. This reduction was specific only for explosive power production not for 1RM, which may represent depression of fast motor units with low fatigue-resistance capacity as well as reflect a more Non-functional fatigue or an overreaching (Meeusen et al. 2012). Along this line, Mujika et al. (2003) concluded that the effect of decreased training volume (decreased to 50-70%) for 7-21 days could result in increases in power production, depending on the individual as well as their training programs and backgrounds. Such events might influence a delayed training effect (Zatsiorsky & Kraemer 2006) as observed in the RFD of P-responders (Fig 2b).

The aforementioned higher initial hormonal levels (Table 2) could also indicate higher tolerance for training, and thus an ability to reach greater power training-induced fatigue and ultimately adaptation (Ryushi et al. 1988). In addition, Ahtiainen and Häkkinen (2009) showed that stronger individuals are capable of producing greater fatigue levels than their weaker counterparts as in Non-responders in this study. Alternatively, the observed reduced fatigue after acute exercise, as well as an unchanged velocity component of power and RFD could be a sign of a greater distribution of slower muscle fibers in the Non-responder individuals. Perhaps the best evidence of this assumption is by the lower responses to muscle stimulation-induced RT parameters. That is, this method primarily activates superficial muscle fibers and thus mainly the fast motor units (Stephens et al. 1978, Garnett & Stephens 1981).

This study was not able to fully explain the origin of lack of adaptation in Non-responders to the training stimuli. Individually tailored training programs might create more effective training outcomes and endocrine responses compared to generic training programs. Ahtiainen et al. (2016) showed that 29 % of traditional resistance trainees were low-responders with regard to gains in muscle size changes, which is in-line with the number of Non-responders (~1/3) during maximum and power strength training segments in the present study. In addition, the data of Haff et al. (2008) showed that 1/3 of their subjects were unable to improve isometric peak RFD; and, their testosterone levels were also not positively adaptive in the changes, although this latter point was not the focus in their study. One limitation of the present study was rather a low number of subjects in each group. It also needs to be noted that the nutritional practices of the subjects were not controlled. However, subjects were instructed to follow national nutrition recommendations, which included guidance on required protein intake for strength training. Furthermore, these nutritional practices were conducted across all the groups, Responders and Non-responders alike.

Conclusions

Strength training induces differences in physiological responses and, thus force production, varied between individuals, which creates a need for tailored training programs. Isometric peak RFD seems to be one useful tool to categorize physical deficiencies of trainee before the planning of a periodized strength training program and monitoring training progress between training sessions. Determination of training session-induced acute responses might be helpful to control the amount and type of fatigue for appropriate adaptation.

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Figure legends

Fig 1. Isometric training monitoring leg extension device.

Fig 2. The changes in a) individual RFD (average of two best time points), b) RFDs in subgroups, c) MVCs in subgroups, and d) MVC normalized RFDs in subgroups during the MS and P training periods.

Fig 3. The average volumes of leg press exercises between sessions at weeks 3½ and 7 during the MS period and at weeks 13½ and 17 during the P period. The averaged acute decreases in RFD and MVC in the bottom and the averaged blood lactate levels in the top of the figure after leg press exercises. * $p<0.05$, # $p=0.056$, ¤ $p=0.068$.

Table legends

Table 1. 1RM leg press, CSA of vastus lateralis muscle and changes in EMG during 1RMs. 1RM baseline (* $p<0.05$) compared to Non-responders. The changes in 1RM and CSA (** $p<0.01$, * $p<0.05$, # $p=0.07$) during 1-10wk and 11-20wk. The changes in large joint angle EMG (** $p<0.01$) during 11-20wk.

Table 2. Basal hormonal levels in subgroups. SHBG and FAI baselines (* $p<0.05$) compared to non-responders. Total and free testosterone, T/C and FAI ratios (* $p<0.05$) during 1-10wk.

Figure

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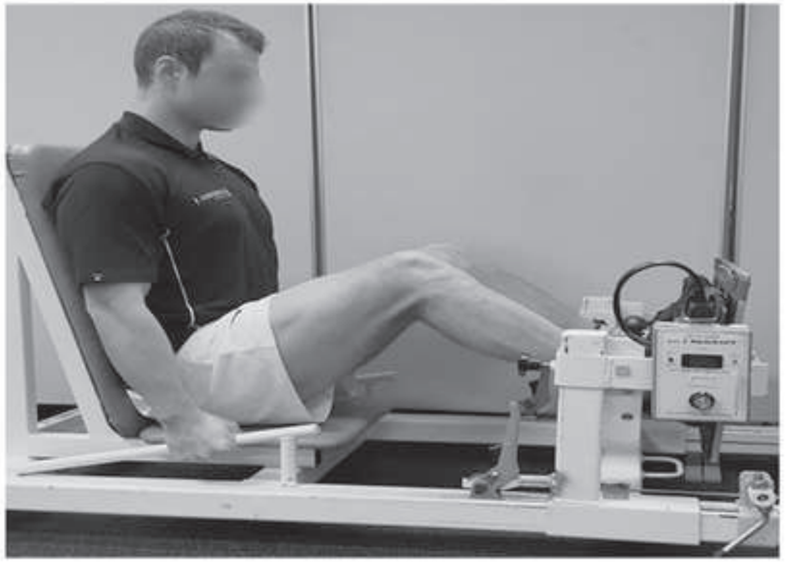
Fig. 1



Figure

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Fig. 2

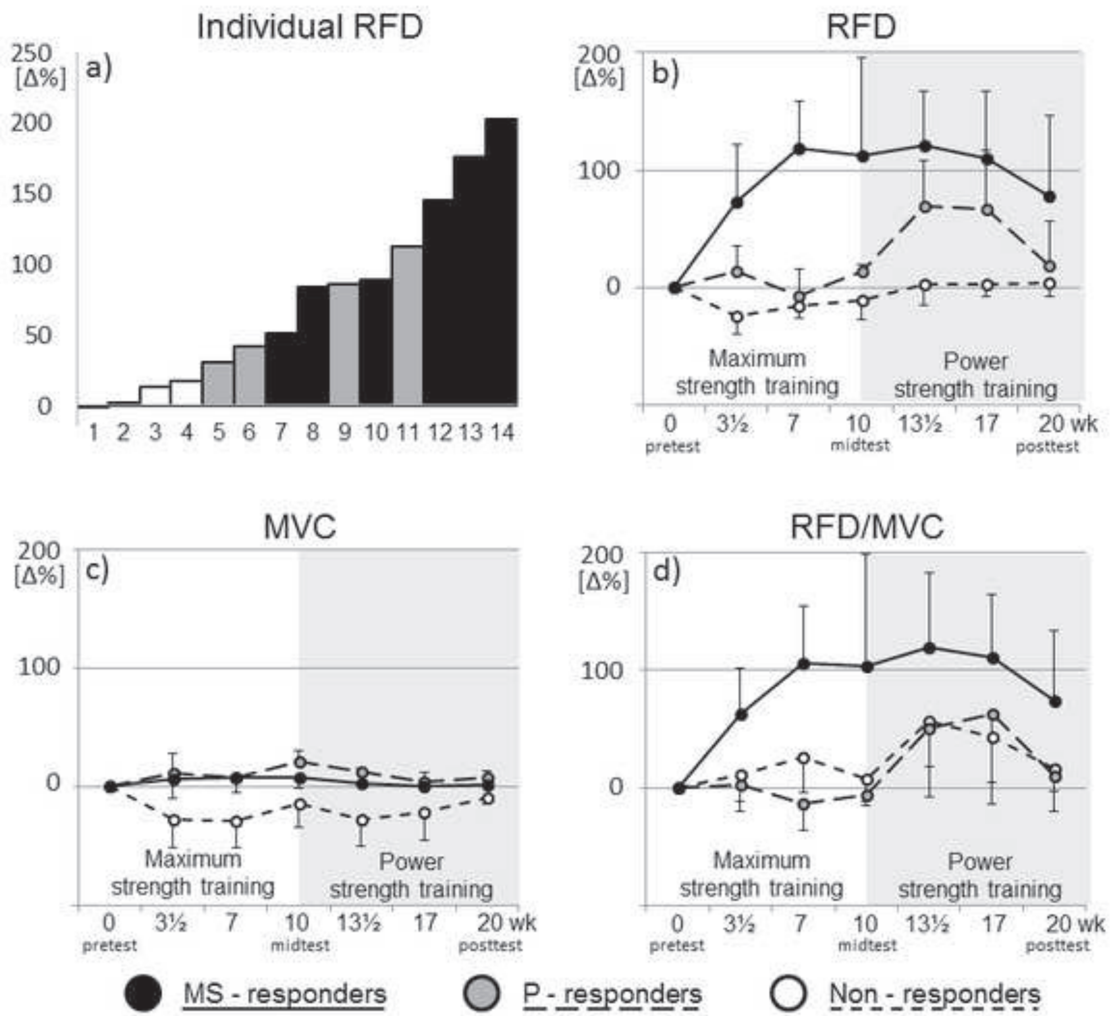

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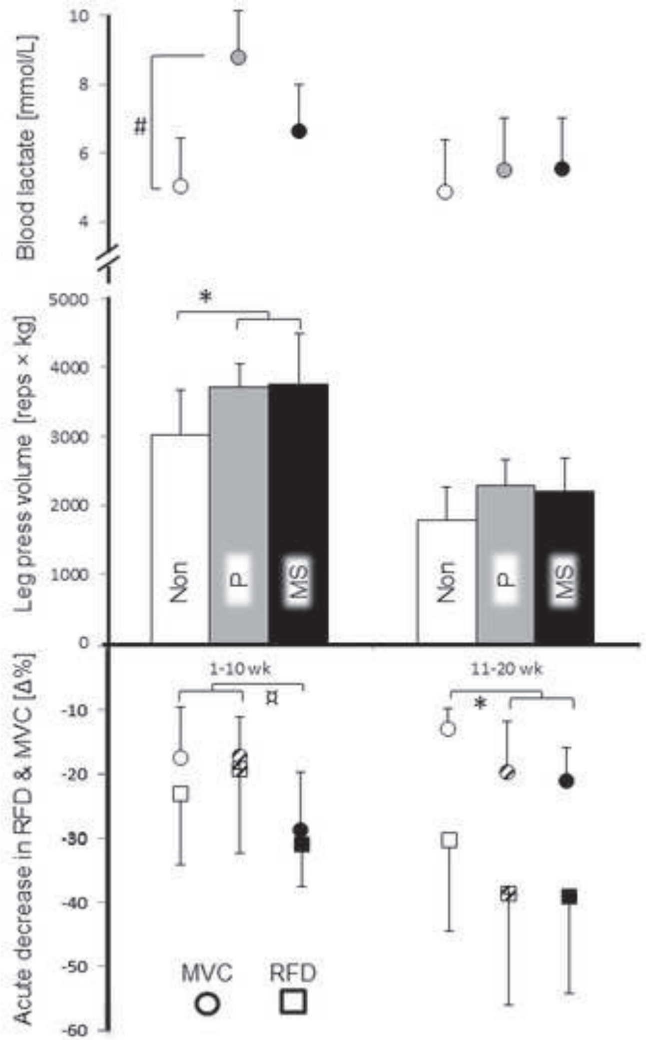
Fig 3.



Table

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Table 1

	Leg press 1RM (kg)			CSA of VL muscle (cm²)			EMG 1RM (Δ%) 60-180°		EMG 1RM (Δ%) 140-160°	
	Pre	10wk	20wk	Pre	10wk	20wk	0-10wk	10-20wk	0-10wk	10-20wk
MS	202±20	* 218±26	227±12	29±7	** 32±6	* 30±2	15±30	-1±19	-6±61	113±76 **
P	178±23	* 193±25	205±18	29±5	# 32±5	# 31±4	1±40	28±45	4±23	6±29
Non	149±21	* 168±21	173±15	23±4	24±9	23±4	15±22	1±28	27±68	29±13

*

Table 2

		MS	P	Non
Cortisol [nmol/L]	Pre	515±163	461±148	622±148
	10wk	539±199	541±115	610±86
	20wk	490±157	573±84	562±88
Total Testosterone [nmol/L]	Pre	26±11	25±12	25±6
	10wk	21±6	19±6	22±6
	20wk	20±9	19±7	19±6
SHBG [nmol/L]	Pre	39±11	27±12	44±5
	10wk	42±13	29±13	45±6
	20wk	40±16	30±15	45±1
Free Testosterone [µmol/L]	Pre	0,43±0,20	0,44±0,21	0,39±0,10
	10wk	0,33±0,11	0,33±0,08	0,35±0,11
	20wk	0,31±0,16	0,32±0,11	0,29±0,11
T/C ratio	Pre	0,060±0,043	0,057±0,023	0,041±0,013
	10wk	0,044±0,022	0,037±0,013	0,036±0,006
	20wk	0,047±0,032	0,033±0,010	0,035±0,010
FAI	Pre	69±28	98±19	56±13
	10wk	51±14	78±34	50±16
	20wk	53±22	70±20	43±14