EFFECTS OF HEAVY RESISTANCE TRAINING ON SHORT-DISTANCE SPRINT PERFORMANCE

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ABSTRACT

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Introduction. Short-distance sprinting is a critical component of physical performance in many sports. Substantial evidence associates sprint performance over the first 30m with the level of maximal strength of an individual. Several authors question the transfer of heavy resistance training (RT) to highly dynamic motor tasks like sprints or jumps. The majority of research focusses on large muscle groups acting as hip and knee extensors during the sprint. A recent study suggests a significant correlation between the maximal strength of the plantarflexors and short-distance sprint performance. The purpose of this study was to examine the effects of six weeks of heavy RT of the plantarflexors in addition to a general RT programme on short-distance sprint times and vertical and horizontal jump performance.

Methods. In total, twenty-one male subjects of varying training status were randomly allocated to an experimental group (EXP; n = 11) and a control group (CON; n = 10). The groups were matched for their one repetition maximum (1RM) in the standing calf raise (SCR) relative to their body mass and their 30m sprint time. Both groups performed 1RM testing of the deep squat and SCR, squat jumps (SJ), countermovement jumps (CMJ), standing long jumps (SLJ) and drop jumps (DJ) and 30m sprints on two separate testing days prior to and after the intervention. The subjects participated in supervised RT sessions including deep squats, bench press, chin ups, SCR (EXP) and overhead press (CON) twice weekly over six weeks. Additionally, the weekly schedule included two aerobic endurance sessions and one speed session.

Results. The groups did not differ significantly from each other any parameter at the start of the intervention. Both groups significantly improved their 1RM in the squat (EXP +13.1%; CON +17.6%) and in the SCR (EXP +11.8; CON +14.8%). The differences between the groups were not significant. The statistical analysis revealed no significant changes in any other parameter.

Conclusion. Heavy resistance training performed twice weekly is sufficient to induce meaningful, significant improvements in maximal strength in the deep squat and the SCR. The lack of significant differences between the groups indicates that the SCR 1RM is potentially invalid in detecting differences in plantarflexion strength. Despite the addition of a weekly session comprising sprints and jumps, the intervention failed to induce statistically significant changes in any other parameters but the 1RM tests. The results implicate that heavy RT can be performed twice weekly without negatively affecting sprint and jump performance.

Key words: Resistance training, plantarflexion, short-distance sprinting, standing calf raise, squat, maximal strength, vertical jump performance, horizontal jump performance

ABBREVIATIONS

1RM	one repetition maximum
ACSA	anatomical cross-sectional area
ANOVA	analysis of variance
CMJ	countermovement jump
CNS	central nervous system
CON	control group
CSA	cross-sectional area
CT	computer tomography
DJ	drop jump
DXA	dual-energy x-ray absorptiometry
EMG	electromyography
EXP	experimental group
FCSA	functional cross-sectional area
GCT	ground contact time
H	jump height
ICC	intraclass correlation coefficient
MRI	magnetic resonance imaging
MU	motor unit
MVC	maximal voluntary contraction
MYH	myosin heavy chain
PCSA	physiological cross-sectional area
PRFD	peak rate of force development
RBE	repeated bout effect
RELSCR	standing calf raise 1RM relative to body mass
RELSQ	squat 1RM relative to body mass
RFD	rate of force development
RSI	reactive strength index
RT	resistance training
SCR	standing calf raise

SLJ	standing long jump
SJ	squat jump
SSC	stretch-shortening cycle
T	flight time during a jump
TMS	transcranial magnetic stimulation

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1 INTRODUCTION

Development and monitoring of short-distance sprint performance is key component of physical preparedness in many sports (Moir et al. 2004; Baker & Newton 2008). Longer ground contact times and high propulsive force characterise the accelerative phase of the sprint. This led scientists and coaches to emphasize the development of maximal strength (Wirth 2011), which correlates well with consecutive segments of the first 30m of the sprint (Möck et al. 2018a). As discussed in Chapter 2, the development of maximal strength depends on morphological and neural factors. Wirth (2011, 131) argues that long-term development of maximal strength requires an increase in muscle size. Increases in muscle sizes inevitably increase body mass, which is potentially detrimental to sprint performance.

Heavy resistance training (RT) elicits a plethora of adaptations on a structural and neural level and a promising method to improve physical performance in various motor tasks (Faigenbaum et al. 2007). In contrast, effective transfer of maximal strength to highly dynamic motor tasks like sprinting has been questioned in the literature (Bührle & Schmidtbleicher 1977; Caroll et al. 2001). While improvements in motor tasks like jumps and throws seem fairly consistent (Behringer et al. 2011), improvements in sprint performance are only marginal (Rumpf et al. 2016). Much of the research has focussed on the performance of the knee and hip extensors. A recent study by Möck et al. (2018b) suggests, for first time, a close relationship between the maximal strength of the plantarflexors and consecutive segments of the first 30m of the sprint. Therefore, the purpose of this study was to examine the effects of heavy RT over six weeks on maximal strength, short-distance sprinting and vertical and horizontal jump performance.

2 BIOLOGICAL BASIS FOR STRENGTH AND POWER

2.1 Definition of strength

Strength refers to a person's or a muscle's ability to generate (maximal) force but requires further description in terms of velocity, type of muscle action, muscles involved or the exercise in which strength is tested (Knuttgen and Komi 2003, 6). Schmidtbleicher (2003, 16) describes maximal strength as the peak force generated by the neuromuscular system in a maximal voluntary contraction (MVC). Maximal strength can further be assessed in concentric, isometric and eccentric contractions. Whilst the velocity at which concentric and eccentric contractions are tested are a topic of debate, the velocity in isometric contractions is zero and therefore, assesses the maximal force generated against an insurmountable resistance (Wirth 2007, 19). When performing a specified exercise, the goal can be to determine the one repetition maximum (1RM), which describes the highest load the subject can lift under the given conditions (Knuttgen & Komi 2003, 6). In isometric contractions, subjects typically reach peak force values after 2.56s (Matkowski et al. 2011) whereas dynamic actions yield peak force values after 150-400ms depending on the load used (Kawamori et al. 2006, 488).

Many studies show considerable correlations between peak force of various muscle groups and sports performance-related outcomes such as acceleration, jumping and throwing (Young et al. 1995; Dowson et al. 1998; Stone et al. 2002; Terzis et al. 2003; Wisløff et al. 2004; Möck et al. 2018a) and sprint cycling (Stone et al. 2004). Wirth (2007, 108) argues that the importance of maximal strength in speed-strength performance, which is essentially the impulse generated in a limited time frame (Schmidtbleicher 1992, 374), depends primarily on the resistance presented by the object to be displaced. This is supported by the notion that correlations between movement velocity and 1RM exist for low loads (0.15 kg, $r = 0.69$, $p < 0.001$), but increase with higher loads (50 kg, $r = 0.91$, $p < 0.001$) (Heyden et al. 1988). Correspondingly, displacement of lighter loads leads to higher velocities and shorter time periods available to generate force and thereby limits percentage of maximal strength that can be used. Since the time period available in the majority of motor tasks rarely exceeds 250ms (Zatsiorsky 1995, 440), many authors argue that the rate at which force is generated gains importance (Aagaard et al. 2002a; 2007; Schmidtbleicher 1992, 374; Rodríguez-Rosell et al. 2018). According to Newton and Kraemer (1994), further increases in maximal strength will not improve performance in activities up to 300ms if athletes have developed a certain level of strength.

Rate of force development (RFD) denotes the change in force produced over the change in time (Δforce/ Δtime) in a given force-time curve from a dynamometric measurement (Aagaard et al. 2002a). In other words, RFD represents the slope of a force-time curve (Bührle & Schmidtbleicher 1977) while peak RFD (PRFD) is the maximum of the first derivative of the force-time function. Unsurprisingly, the length of the time interval, over which the change in force is obtained, is a matter of debate (Haff et al. 2015). Whilst some studies analyse intervals from onset of force production to specified time points (Andersen & Aagaard 2006), most determine PRFD from intervals of 2ms to 60ms (Christ et al. 1993; Haff et al. 2015). Haff et al. (2015) promote the use of a 20ms interval since it was more reliable than shorter or longer intervals. The number and length of time intervals available is generally restricted by the sampling rate of the measurement device but as Rodríguez-Rosell et al. (2018) point out, it should reflect the physiological context of the analysis.

Substantial evidence links RFD to motor tasks like short-distance sprinting, jumping (Wilson et al. 1995; Tillin et al. 2013) as well as outcomes in clinical settings (Maffiuletti et al. 2010; Angelozzi et al. 2012). Since most sporting action are highly dynamic in nature and involve the displacement of the body or objects at high velocities, one might question the use of isometric assessments as determinants of sport performance. In fact, some authors report a lack of significant correlations between peak force or RFD and short-distance sprinting (Mero et al. 1981; Wilson et al. 1995). Next to maximal strength and RFD, power production is held as a main predictor in sports featuring high acceleration values seen in sprinting, jumping and throwing (Newton & Kraemer 1994, 20). Power is the product of force and distance over a time interval ((force x distance)/ time) or in other words the product of force and velocity (force x velocity) and is expressed in watt (W).

It might appear as if these three parameters are independent entities, which are on the same hierarchical level. If this was the case, an athlete could develop high levels of one of them without affecting another. It would also imply that there are only weak correlations between them. However, correlations between maximal strength, RFD and power seem to be relatively consistent (Baker 2001; Carlock et al. 2004; Andersen & Aagaard 2006). Cross-sectional correlations in athletic populations may still not be able to proof that these three parameters are interdependent since one might argue that athletes' programmes usually include several different methods to develop a number of different qualities. In review of the morphological and neural determinants, it becomes obvious that the parameters share similar mechanisms with some aspects being more relevant for one parameter than for another. Some authors highlight the idea that maximal strength is a basic requirement of the development of a high RFD and consequently power production. Therefore, it shall not surprise the reader that an increase in maximal strength increases performance in motor tasks of less than 250ms, as will be discussed in later chapters.

2.2 Neural determinants

The force an individual can exert presents the sum of all excitatory and inhibitory signals from the central nervous system (CNS) including the spinal cord to the agonistic, synergistic and antagonistic muscles. In activities of daily living or sporting events, movements are rarely the result of an isolated contraction of a muscle but require careful coordination of all muscles involved in maintenance of balance while parts of the body or objects are accelerated with a specific trajectory (Wolpert et al. 2003, 752).

The neural drive to a muscle can be quantified in terms of recruitment and rate coding. Recruitment describes the number of motor units (MU) activated in a contraction whereas rate coding describes the frequency at which alpha motoneurons discharge (firing rate). An increase in the number of MUs recruited or increase in the discharge rate leads to increase in force produced (Moritani 2003, 30). Since motor units differ in size and the number and phenotype of muscle fibres they innervate, smaller MUs discharge earlier, i.e. have a lower threshold and at lower forces during a contraction. Henneman et al. (1965) coined the term `size principle´ based on their observations in cat motoneurons, which seemed to fire in almost all cases in a specific order according to their size.

Milner-Brown et al. (1973) confirmed the results by Henneman et al. (1965) and reported that with increasing force the number of additional MUs decreases, leading them to conclude that recruitment loses importance at high levels of force. In fact, the level of force at which no further recruitment was recorded varies between muscles but the highest was 88% MVC in biceps brachii (Kukulka & Clamann 1981). Based on the assumption of an unequal distribution of MUs, Duchateau and Enoka (2011) summarise:

> "These findings indicate that motor unit pools comprise many low-threshold motor units and fewer high-threshold motor units (Thomas et al., 1986; Van Cutsem et al., 1997), which suggests that the control of force during slow, low-force contractions relies mainly on the recruitment of motor units (Enoka, 1995; Fuglevand et al., 1993; Heckman and Binder, 1991).

Additionally, Desmedt and Godaux (1977) observed a notable reduction in recruitment threshold when isometric contractions were performed with the intention to maximize the rate of force development, termed ballistic contractions. They also noted that motoneurons discharged at much higher frequencies during ballistic contractions (60-120/s), followed by a sharp decline, compared to ramp contractions, which feature an initial frequency of 5-15/s and slight increase to 30/s with increasing force levels (1977, 680). Even higher frequencies (286Hz) occur during so called doublet discharges when MUs fire twice with an interspike interval up to 5ms (Van Cutsem et al. 1998)

Several authors highlight the importance of the neural drive especially to rate of force development (Maffiuletti et al. 2016; Blazevich et al. 2009). Folland et al. (2014) investigated the determinants of RFD in knee extension and concluded that neural activation accounted for 21-51% of variance in relative RFD between individuals between 25ms and 75ms after contraction onset. An increased neural activation was also shown to increase peak force (Häkkinen et al. 1985). Whilst for RFD it seems logical to synchronise firing of as many MUs as possible, Sale (2003, 290) argues that asynchronous firing might be advantageous to for peak forces. In conclusion, neural activation is undisputedly an important factor in force production with varying contribution along the force-time-curve.

2.3 Morphological determinants

Since neural determinants can explain the variance in strength capacity only partially, other factors must play important roles. Anatomical differences such as limb length, tendon insertion points and joint mechanics are able to explain interindividual differences but will not be discussed in this review as they are constant over time. More importantly, the muscle-tendon unit comprises parallel- and series-elastic components presenting interindividual variability as well as high plasticity.

Firstly, the most obvious aspect is muscle mass, which authors often discuss as cross-sectional area (CSA), since two-dimensional assessment is much more feasible than three-dimensional assessment of volume or mass. Wirth (2011, 125) considers muscle CSA as a foundation for the development of maximal strength. Correlations between body mass and performance in weightlifting and powerlifting would support this statement if it can be assumed that the higher body mass is mainly due to higher muscle mass (Stone et al. 2006). Numerous cross-sectional studies report strong relationships between CSA or muscle volume and maximal strength capacity (Kanehisa et al. 1994; Bamman et al. 2000; Fukunaga et al. 2001). Since RFD depends on maximal strength and this in turn depends on muscle mass, correlations between power output and CSA are expected (Moss et al. 1997). Longitudinal studies, such as one from 2014 by Erskine et al. (2014), show that gains in hypertrophy can explain the variance in gains in peak force but less in RFD.

Secondly, skeletal muscle also varies in its intrinsic contractile properties. Muscle fibres can be further characterized by their myosin heavy chain isoform phenotype, which led scientists to distinguish mainly between type I, type IIA and type IIX fibres in human muscle (Enoka & Duchateau 2015). Histochemical analysis also involves myosin ATPase staining to identify the corresponding fibre type (Schiaffino et al. 2007). Fibres of type II have higher shortening velocities and higher power output with type IIX having the highest (Bottinelli et al. 1996). Bosco and Komi (1979) studied the relationship between percentage of fast twitch fibres and performance in two vertical jump tests and found significant positive correlations ($r = 0.37$ and $r = 0.48$). In contrast, longitudinal studies often show increases in RFD and/or power output despite decreasing or unchanged percentage of type 2X fibres, whereas the fibre area increased (Häkkinen et al. 2003). This finding highlights that not only the number of fibres determines performance but also the area a fibre type covers. More recently, researchers started to appreciate the variability of the type of myosin heavy chain (MYH) isoform expressed within a single fibre (Schiaffino & Reggiani 2011; Prats et al. 2013). Single fibre analysis, performed by Murgia et al. (2017), revealed that 76% of slow fibres and 79% of fast fibres expressed to at least 80% only one type of MYH. This implicates that a considerable amount of fibres can attain qualities more pronounced in fast or in slow fibres at the same time. Therefore, studies investigating fibre types in relation to exercise traits should be interpreted cautiously.

Lastly, the force produced by the muscle needs to be transmitted effectively to the skeleton by the tendon. The tendon as a series-elastic element can vary in stiffness, therefore vary in its ability to store and release kinetic energy. Bojsen-Møller et al. (2005) used ultrasonography to measure the mechanical properties of the tendon-aponeurosis complex of the vastus lateralis and assessed neuromuscular performance in isometric knee extension, countermovement jump (CMJ) and squat jump (SJ) in highly trained men. The stiffness correlated with RFD of the first 100ms ($r = 0.54$) and 200ms ($r = 0.56$) of the isometric MVC as well as with jump height in the SJ ($r = 0.64$) and CMJ ($r = 0.55$). This data indicates that mechanical properties are another important factor, perhaps mainly for performance of short time intervals.

3 PHYSIOLOGICAL ADAPTATIONS TO RESISTANCE TRAINING

Strength training, more general RT describes repetitive muscular contractions against higher loads in a systematic fashion. Commonly used variables such as intensity as the percentage of 1RM, volume as the product of number of sets and number of repetitions and weight lifted, rest period between sets or frequency allow precise characterisation of RT protocols. Protocols proven to cause long-term effects on physiological parameters can vary dramatically but often share several core principles: progressive overload, specificity and the repeated bout effect (RBE). These core principles suggest that the training process follows a progressive change in one of the above-mentioned variables in a way that the bout of exercise presents a stimulus to the system. The RBE implies that skeletal muscle becomes less susceptible to exercise-induced muscle damage and initiates multiple protective mechanisms after just one bout of exercise (Hyldahl et al. 2017). Although adaptations and responses to RT can be highly specific to the protocol (Behm & Sale, 1993; Hulmi et al. 2012), RT elicits an orchestra of signalling mechanisms in a variety of organ systems, which will be briefly discussed in this chapter.

3.1 Morphological adaptations to strength training

The muscle-tendon unit consists of series- and parallel-elastic components, which are able to adapt structurally in response to RT. These physiological responses often translate to changes in functional properties and can affect performance positively. Since the turnover rates in different tissues vary, smaller changes might be harder to detect by the available measurement instruments after only short training periods. A lack of reliability, validity and comparability in certain measurement tools has led to a number of contrasting results in the past (Haun et al. 2019).

3.1.1 Changes in muscle size

Scientific studies frequently demonstrate the skeletal muscle's ability to grow in size in response to RT, a phenomenon called hypertrophy. Researchers commonly use ultrasonography, magnetic resonance imaging (MRI), computed tomography (CT) or dual-energy x-ray absorptiometry (DXA) to assess several different parameters such as CSA, functional CSA (FCSA) or muscle thickness on a macroscopic level. In a recent meta-analysis, Schoenfeld et al. (2017) concluded that lighter loads (≤60% 1RM) led to similar gains in muscle size (7% vs. 8.3%) compared to higher loads (>60% 1RM). Another systematic review compared RT intervention outcomes in muscle growth regarding the weekly volume and found that higher weekly volumes (10+ sets/week) appear to be superior (Schoenfeld et al. 2017). Although gains in muscle size occur in various populations, substantial evidence points out that the response to RT may vary drastically between individuals (Ahtiainen et al. 2016).

Research suggests changes in muscle size after six (Luethi et al. 1986; Bell et al. 1991; Abe et al. 2000), eight (Narici et al. 1989; Kersick et al. 2009) and ten weeks in upper but not lower body muscles (Chilibeck et al. 1998). Interestingly, a study by Cureton et al. (1988) also found changes in CSA after 16 weeks of RT in the upper body but not lower body muscles. This suggests that the upper body muscles adapt faster than the lower body muscles, which could be explained by the use of those muscles during activities of daily living.

3.1.2 Changes in muscle architecture

Pennation angle and muscle fibre length mainly determine a muscle's architecture and influence the force-velocity relationship. The pennation angle refers to the angle at which muscle fibres attach to the tendon or aponeurosis and is an important factor when relating CSA to a muscle's force capacity. Whilst anatomical CSA (ACSA) measures the cross section perpendicular to the longitudinal axis of the muscle, physiological CSA (PCSA) accounts for changes in pennation angle by measuring the cross section perpendicular to the muscle fibres. An increase in pennation angle often accompanies muscle growth, can be contraction-specific and possibly is a function of addition of sarcomeres in parallel (Franchi et al. 2017). Theoretically, an increase in the number of sarcomeres allows for a greater force-generating capacity (Fukunaga et al. 2001). From a biomechanical standpoint, an increase in pennation angle would decrease the force transmitted to the tendon or aponeurosis since this force is proportionate to the cosine of the pennation angle (Degens et al. 2009). Aagaard et al. (2001) conducted a study in which eleven male subjects performed 14 weeks of heavy RT of lower body muscles and assessed pennation angle, ACSA and PCSA. Pennation angle changed from 8° to 10.7° (+35.5%) and ACSA increased by 10.2%, whereas individual fibre CSA increased by 16% and MVC torque by 16%, as well. These results highlight that gains made by an increased PCSA outweigh the reduction in force transmitted to the tendon caused by an increase in pennation angle.

3.1.3 Changes in muscle fibre phenotype

As discussed previously, physiologists distinguish between three fibre types, the oxidative, slow-twitch type I and the glycolytic, fast-twitch types IIA and IIX (Enoka & Duchateau 2015). In the developmental stage, genetics and thyroid hormones determine the skeletal muscle fibre phenotype and later, neural activity further contributes the muscle fibre's plasticity. In review of the available literature, Fry (2004) came to the conclusion that chronic RT promotes a shift from type IIX (IIB) to type IIA relatively independent of the intensity used (40-95% 1RM) with the percentage of type I fibres unaltered. Studies that are more recent support this conclusion with the addition that type IIX levels may increase after a subsequent detraining phase (Andersen et al. 2005; Andersen et al. 2010). Pareja-Blanco et al. (2017) made an interesting observation when they compared the results of two groups performing RT over eight weeks. They instructed one group to terminate the set when the mean propulsive velocity of the repetition dropped to 80% of the initial velocity and the other group at 60%. As expected from previous studies, the group that trained closed to failure (40% velocity loss) decreased their percentage of type 2X fibres, whereas the other group maintained their percentage of type 2X fibres. This novel approach indicates that more research is needed to explain the effects of RT variables on fibre phenotype changes. On the other hand, recent advantages in technology highlight the complexity of identifying distinct fibre types (Schiaffino & Reggiani 2011; Murgia et al. 2015).

3.1.4 Changes in connective tissue

For a long time, scientists considered the tendon being relatively inert to mechanical loading (Kjaer et al. 2008; Magnusson et al. 2008). In the past years, our understanding of tendon adaptation improved dramatically and numerous studies showed increases in tendon and tendon-aponeurosis stiffness after eight weeks of RT (Kubo et al. 2002), twelve weeks of RT (Kubo et al. 2006; Kubo et al. 2007) and 14 weeks (Reeves et al. 2003). Kongsgaard et al. (2007) also found increased stiffness after twelve weeks of RT and additional increases in CSA in the proximal and distal but not the mid part of the tendon. A systematic review by Wiesinger et al. (2015) revealed that patellar and Achilles tendons adapt similarly and that RT was more effective than other types of exercise. Furthermore, they concluded that changes in mechanical properties might occur after only six to eight weeks of training in the absence of tendon hypertrophy, which occurs later.

3.2 Neural adaptations to strength training

Since force output is the result of the descending drive to the agonistic, synergistic and antagonistic muscles, increases in strength are the result of adaptive responses on a spinal and supraspinal level. The majority of studies use surface electromyography (EMG) to gain insights into neural activation and signal propagation throughout the muscle with questionable validity (Farina et al. 2014). Transcranial magnetic stimulation (TMS) and peripheral nerve/muscle electrical stimulation are methods to detect changes on different levels of the MU and the CNS. In theory, changes in force output must result from changes in recruitment of MUs, discharge rates or synchronisation of MU firing.

A number of different studies reported increases in neural activation in response to eight to 16 weeks of heavy RT (Häkkinen & Komi 1983; Narici et al. 1989; Aagaard et al. 2002a; 2002b). Considering that recruitment does not increase above ~88% MVC (Kukulka & Clamann 1981), higher discharge rates are more likely to explain higher levels of activation obtained by EMG (Walker 2018, 81). Intramuscular EMG recordings provided evidence for increased MU discharge rates after six weeks of progressive RT in younger (+11.4%) and older adults (+47%) (Kamen et al. 1998) as well as after twelve weeks of low load RT (30-40% 1RM) in younger adults (Van Cutsem et al. 1998). More recent technologies allowed the identification of adaptive mechanisms by using high density EMG to record activity of the same set of motor units at different time points (Farina et al. 2016). Del Vecchio et al. (2018) observed lowered recruitment threshold as well as higher discharge rates during submaximal contractions after four weeks of training of the tibialis anterior muscle. These changes occurred concomitantly to increased MVC force. Evidence for increased synchronisation of MUs is very limited (Milner-Brown, Stein, Lee 1975, 252) but this might be due to methodological issues.

Since the descending drive can be modulated on a spinal or supraspinal level, Kidgell, Stokes, Castricum and Pearce (2010) sought to determine the effects of 4 weeks of heavy RT (80% 1RM) on corticospinal conduction and excitability. They concluded that RT increases corticospinal excitability but they cannot exclude inputs from other neural circuits. Further studies are needed to identify and quantify the sites of neural adaptations but it is most likely that changes occur on both spinal and supraspinal level result in an increased descending drive, increased motoneuron excitability and reduced presynaptic Ia afferent inhibition (Aagaard et al. 2002b; Del Balso & Cafarelli 2006).

3.3 Adaptations in motor tasks

Apart from the more direct measures of physiological constructs, strength-related outcomes such as peak force, 1RM or RFD serve as indirect measures of increased voluntary activation or gains in muscle mass. An important issue occurs when assessing changes in different motor tasks or testing conditions is the transfer problem (Wirth 2011, 56). It is also a topic of debate among coaches if an increase in maximal strength in general RT exercises like the barbell squat translates to increase in other motor tasks like jumps or throws. Increases in 1RM and isometric MVC are convincingly consistent observations in studies using dynamic resistance training at varying loads, tend to be larger at higher intensities (Schoenfeld et al. 2017) but can range from -8% to +60% (Ahtiainen et al. 2016, 5). On the other hand, several studies highlight the specificity of adaptations to RT concerning the type of muscle action, the joint angles and the velocity at which subjects train (Lesmes et al. 1978; Pearson & Costill 1988; Abernethy & Jürimäe 1996; Sale, Martin, Moroz 1992; Hartmann et al. 2012). One issue of these studies is that the populations studied are mainly untrained.

Apart from a lack of transfer, Carroll et al. (2001) point out that even negative transfer, meaning improvements in the training exercises reduces performance in another motor task, can occur.

As a general principle, positive transfer is more likely to happen if the improved motor pattern of the RT exercise translates well to greater excitatory activation of the muscles recruited in the transfer task. Another important factor is the training history and the performance level of the populations studied considering that improvements in well-trained athletes are only marginal and occur only after long periods of training (Häkkinen 1985; Häkkinen et al. 1988). It seems reasonable to expect larger improvements in maximal strength in untrained subjects than in athletes, therefore, the transfer to other motor tasks can be expected to be better (Wirth 2011, 69).

In a number of studies researchers showed that increases in maximal strength from RT improved vertical jump performance after six (Adams et al. 1992; Augustsson et al. 1998), eight (Channell & Barfield 2008), ten (Hartmann et al. 2012) and twelve weeks (Anderst et al. 1994; Fatourus et al. 2000). In addition, the literature would suggest that a combination of RT and plyometric training elicits greater gains in motor performance, at least in adolescents (Faigenbaum et al. 2007; Behringer et al. 2011; Lloyd et al. 2016). Aagaard et al. (1994) published a study for which they divided 24 male elite soccer players into three training groups and one control group. One group trained with high loads and at low velocities, one group with low loads and at high velocities and one group performed loaded kicking movements. The authors assessed several parameters before and after twelve weeks of training and found that high load training improved mechanical power output at all tested velocities and more than the other RT regimes (1994). Moss et al. (1997) found similar results for the elbow flexors. In summary, the body of evidence allows the conclusion that RT and the concomitant increase in maximal strength transfers well to different motor tasks. This conclusion has limited validity since the majority of studies do not investigate highly trained individuals for whom careful consideration of training methods is critical. On the other hand, motor tasks such as jumps and throws rarely occur in isolation in sports and are subject to various restrictions and influencing factors. Therefore, it is less clear if increases in strength serve its purpose of improving sports performance.

4 SPRINT RUNNING AND RESISTANCE TRAINING

4.1 Biomechanics of sprinting

The course of a maximal sprint is characterised by an acceleration phase, a maximum velocity phase and a deceleration phase (Mero et al. 1992). Several biomechanical variables such as muscle activation, stride length, stride frequency, ground contact time and flight time change throughout the three phases. Several studies analysed the start of the sprint from blocks (Mero et al. 1992; Salo et al. 2017) but since this work analyses sprints from a standing start, the discussion of the block start is not part of it. The accelerative phase extends over 30 to 50 meters with increasing stride length and frequency and decreasing ground contact times (Mero et al. 1992, 380) and discriminates faster from slower sprinters (Letzelter 2006). According to Mero et al. (1992), stride length and frequency increase linearly to speeds of 7 m/s after which the increase in stride frequency determines an increase in velocity. During the first few steps, ground contact times are between 150 and 250ms (Mero 1988) and decrease to only 80 to 100ms during the maximum velocity phase (Zatsiorky & Kraemer 2006, 27).

Based on ground reaction forces, scientists divide the stance phase into a breaking phase during which the body's centre of gravity lowers and a propulsive phase during which it rises again. The distribution between the breaking and propulsive phase changes throughout the sprint. During the early accelerative phase, the breaking phase makes up for only a small part of the stance phase and the propulsive phase predominates (Mero 1988), which is not surprising, since acceleration comes from high propulsive forces. At maximum velocity, the breaking phase comprises almost half of the stance phase and forces become equal (Haugen et al 2019).

Scientists and coaches emphasised muscle activity obtained from surface EMG recordings during the different phases of the gait cycle (Mero et al. 1992; Howard et al. 2016). As mentioned previously, the use of surface EMG to make assumptions about muscle activity bears several methodological issues (Farina et al. 2014). A recent study by Péter et al. (2019) compared EMG signals obtained from lower leg muscles using fine-wire technology to those using surface EMG at different walking speeds. They found differences for several muscles across different walking speeds, which shows that EMG data should be interpreted cautiously in general but especially during highly dynamic movements (Farina 2006). Hegyi et al. (2019) found, using high-density EMG, increasing muscle activity with increasing running speeds in hamstring muscles and it peaked during the late swing phase and early stance phase. More importantly, they identified highly individualised activation patterns of the recorded muscle, which suggests that averaging EMG values across subjects might be inherently flawed. Kyröläinen et al. (2005) found increasing EMG activity in the leg extensor muscle with increasing running speed, which was far above activation levels recorded from MVCs.

4.2 Determinants of sprinting performance

Since running velocity is the product of stride length and stride frequency, these two factors or much more the optimal ratio of them is the most prominent determinant of sprinting performance. Apparently, researchers have not agreed on which of the two parameters is more important to performance but longitudinal data from a world class sprinter would support the notion of Mero et al. (1992) that an increase stride frequency leads to further increases in performance (Bezodis et al. (2008). In an attempt to summarise the neural and morphological determinants of stride length and stride frequency, Ross et al. (2001) published the scheme seen in FIGURE 1. Most of the named factors are covered in detail in earlier chapters.

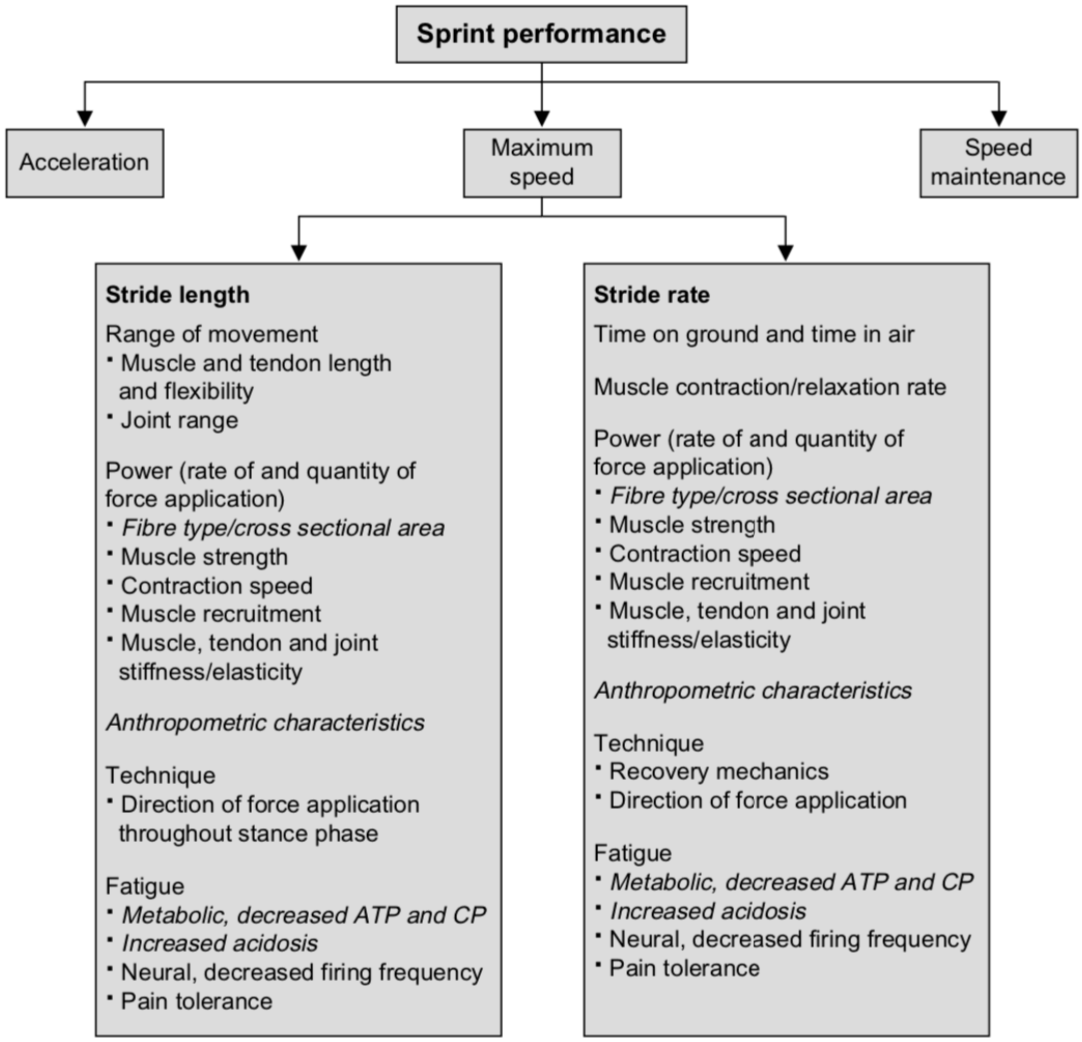

FIGURE 1. Neural and morphological determinants of maximum speed (Ross et al. 2001).

From the push-off, the goal is to accelerate as quickly as possible, therefore, the ratio of braking and propulsion must favour propulsion to generate horizontal velocity (Haugen et al. 2019). Colyer et al. (2018) analysed the ground reaction force waveforms of 28 male track and field athletes along the first 24 steps of maximum sprints. Their primary finding was that the average external power produced during the early accelerative phase was strongly associated with anterior-posterior force production during 58-92% of the stance phase. With increasing velocity and decreasing ground contact times, anterior-posterior forces earlier during the stance phase (19-64%) correlated with average external power. These results and consideration of the longer ground contact time during the first few steps suggest that the ability to produce high forces is critical to sprint running:

> "The high correlation coefficient (r = 0.74; n = 8; Mero 1988) between the propulsive force and running velocity during the first contact after the blocks further emphasises both the character of the propulsion phase and the import-ance of strength during the acceleration phase of sprinting." (Mero et al. 1992)

Numerous studies support this notion by reporting medium to high correlations between maximal strength in the squat and performance in the accelerative phase of the sprint (Heyden et al. 1988; Wisløff et al. 2004; McBride et al. 2009; Keiner et al. 2014; Möck et al. 2018a). Studies in which the investigators used the 3RM in the squat as a test for maximal strength did not find correlations with short-distance sprinting performance (Baker & Nance 1999; Cronin & Hansen 2005). This is less surprising considering the uncertainty of the percentage of the 1RM, a 3RM load presents (Wirth 2007, 14). Since the importance of maximal strength decreases with shorter time periods available for force production (see chapter 2), RFD and the underlying neurophysiological mechanisms become increasingly relevant with higher velocities and shorter ground contact times.

Kyröläinen et al. (2005) argue that the higher pre-activity observed in the leg extension muscles at higher velocities leads to higher activation during the breaking phase and increased stiffness. This would be more important for the later phases of the sprint when ground contact times are shorter and the breaking phase is relatively longer. One important mention is the observation of the short latency reflex, which occurs shortly upon stretching of the fascicles and induces force potentiation. Ishikawa and Komi (2007) showed that the contribution of the reflex shifts towards the propulsive phase of the stance during running compared to walking speeds. A more recent study by Möck et al. (2018b) investigated the relationship between the maximum strength of the plantarflexors and the sprint performance in sections up to 30 meters. The 1RM in the standing calf raises (SCR) correlated medium to well (r = -0.483 to -0.720) with consecutive 5-meter-intervals of the 30-meter sprint. The correlations between 1RM relative to body weight and sprints were similar (r= -0.460 to -0.577). One should note that the researchers obtained these results from a heterogenous sample, which did not include high level sprint athletes. Nevertheless, these results support the notion that sprinters have higher tendon stiffness (Arampatzis et al. 2007) and high levels of activation are necessary to resist the stretch upon ground contact (Komi 2003, 199). Therefore, it is not surprising that maximal strength of plantarflexors correlates significantly with performance in stretch-shortening cycles (SSC) during drop jumps (Hartmann et al. 2017), which show high correlations with sprint performance (r = -0.684 to -0.79) (Hennessy & Kilty 2001; Cunha et al. 2007).

4.3 Effects of resistance training on sprint performance

As discussed extensively in earlier chapters, compelling evidence from theoretical and cross-sectional data highlights the importance of high levels of maximal strength for sprint running, primarily the accelerative phase. Only few longitudinal studies exist that investigate the effects of RT on sprint performance. The results are summarised in Table 1.

TABLE 1. Studies investigating the effects of heavy* RT on sprint performance

Publication	n	Intervention	Outcome	Performance change
Delecluse et al. 1995	22	RT; 9 weeks, 2x/wk; full body; 3-4 x 3-10RM/ exercise	100m sprint time; 0-10-m acceleration	ns; s
McBride et al. 2002	10	RT; 8 weeks, 13.4 sessions; jump squats 80%1RM 5RM/exercise + sprinting	0-5m; 0-10m: 0-20m sprint time	+7; +4.4; +1.8
Blazevich & Jenkins 2002		RT; 7 weeks, 2x/week lower body + 1x/week upper body; 70-90%1RM, 4 x 10-3 repititions	20m sprint time; 20m "flying" sprint time	-2.9%; -2.4%
Moir et al. 2007	10	RT; 8 weeks, 3x/wk; full body; 3 x 12-5RM/exercise + sprinting	0-10m; 10-20m; 0-20m sprint time	+6%; -7%; ns
Styles et al. 2016	17	RT; 6 weeks, 2x/week; 3-5 x 3-6 85-90%1RM + speed training	0-5m; 0-10m; 0-20m sprint time	-5%; -3%; -1%

*Only RT studies employing intensities equivalent to 12RM/70%1RM or higher were included.

This short overview exemplifies that despite the critical role of maximum strength for the development of speed, an increase in maximum strength induced by heavy RT does not transfer to increased sprinting performance in all cases. As discussed in 3.3, transfer depends on a number of factors and is more likely to occur for less complex motor tasks such as jumps. Some authors argue that a transfer from maximal strength to sprint running might involve a certain lag time, which these studies usually do not consider. In a recent review, Rumpf et al. (2016) concluded that strength training will only have a small effect on short-distance sprint performance, however, the inclusion criteria remain fairly unclear to the reader.

5 AIMS OF THE STUDY

The purpose of this study was to examine the effects of heavy RT and short-distance sprint performance and other performance-related outcomes. Heavy RT elicits a variety of morphological and neural adaptations. In the majority of subjects, these adaptations lead to increases in maximum strength (Ahtiainen et al. 2016, 5). Typically, subjects in these studies train large muscle groups involved in locomotion such as the knee and hip extensors. According to the knowledge of the author, no studies used the 1RM as a test to detect changes in maximum strength of the plantarflexors.

Question 1. Do six weeks of heavy RT twice weekly improve the 1RM in the SCR?

Hypothesis 1. Six weeks of heavy RT twice weekly improve the 1RM in the SCR.

The analysis of the current literature implicates difficulties of transferring gains in maximum strength to complex motor tasks like sprinting (Carroll et al. 2001; Rumpf et al 2016). Häkkinen (1985) argues that the transfer that one can expect depends on the training history among other factors. Likewise, Wirth (2011, 69) points out that the magnitude of increase in maximum strength determines the magnitude of transfer, which is higher in untrained people. The plantar flexion muscles of the lower limb are generally exposed to high amounts of loading, since they are involved in any upright movement. However, heavy dynamic RT might present an unaccustomed training stimulus that potentially elicits greater gains than exercises the subjects of this study are already used to. For the first time, Möck et al. (2018b) reported medium to high significant correlations between the 1RM in the SCR and the sections of a 30-meter sprint. Thus, this study sought to determine the effects of heavy plantar flexion training on sections of a 30-meter sprint.

Question 2. Do six weeks of heavy RT of the plantarflexors of the lower limb twice a week improve short-distance sprinting performance?

Hypothesis 2. Six weeks of heavy RT of the plantarflexors of the lower limb twice a week decreases time to 20m, 30m, 5-10m, 10-15m, 20-30m of sprint.

Numerous studies showed improvements in vertical jump performance (Adams et al. 1992; Augustsson et al. 1998; Channell & Barfield 2008; Hartmann et al. 2012). A recent study by Pallarés et al. (2019) showed that even after ten weeks of heavy RT, the CMJ and time to 20m in the sprint improved but only the CMJ significantly. These results suggest that improvements in motor tasks like vertical jumping can occur in the absence of improvements in the sprint. As discussed in 4.2, pre-activity of the plantarflexors improves stiffness regulation, which would be important for transfer of force from the muscle-tendon unit to the skeleton and the ground and thus, performance in jumps, especially the drop jump (DJ).

Question 3. Do six weeks of heavy RT of the plantarflexors of the lower limb twice a week improve vertical and horizontal jump performance?

Hypothesis 3. Six weeks of heavy RT of the plantarflexors of the lower limb twice a week increases jump height in the SJ, CMJ and DJ, decrease ground contact time during the DJ and increase distance in the standing long jump (SLJ).

6 METHODS

6.1 Subjects

Initially, 30 male A-junior floorball players from the local floorball club (Happee Ry, Jyväskylä) were recruited at the beginning of their off-season to participate in the project. Only subjects participating in all of the training sessions of the A-junior team were included. Subjects with injuries in the last 3 months were excluded. Nine subjects failed to participate in all pre-tests and were excluded from the project. A total number of 21 subjects began the training period of which five dropped out due to insufficient number of training sessions (less than 9/12 sessions). The reasons for missing a training were either sickness (most likely unrelated to the intervention), injury (unrelated to the intervention) or personal reasons (unrelated to the intervention). For reasons of convenience and development of the individual, it was decided to exclude the subjects from the post-tests, who failed to meet the minimum required number of training sessions. The majority of subjects were accustomed to the exercises performed during the testing and the intervention and Table 2 presents the descriptives of the subjects. The subjects and their legal representatives were informed about the design of the study and possible risks involved and gave their informed consent prior to the study. The study was approved by the ethical committee of the University of Jyväskylä, Finland (07.05.2019).

TABLE 2. Anthropometrics of the subjects.

	N	Age	Height (m)	Body mass (kg)
EXP	11	17.2 ± 1.5	1.79 ± 0.06	73.7 ± 13.0
CON	10	17.1 ± 1.7	1.80 ± 0.08	74.8 ± 11.5
Total	21	17.1 ± 1.6	1.80 ± 0.07	74.2 ± 12.0

Values are presented as means ± standard deviation. EXP, experimental group; CON, control group.

6.2 Study design

To study the effects of heavy RT of the plantarflexors of the lower limb on short-distance sprint performance and other performance-related outcomes, subjects were divided into a control group (CON) and an experimental group (EXP). Prior to the training period, subjects performed several tests on two days. The participants were instructed to rest during the 72 hours between testing days and repeated the same procedure one week later. During the six weeks of intervention, subjects participated in two supervised RT sessions, two supervised aerobic endurance training sessions, two floorball training session and one supervised speed training sessions. After the training period, the subjects participated in the same testing procedure as prior to the training period. Due to special events involving friendly games, the schedule exhibited some minor changes in one week in which the second aerobic endurance training session was cancelled.

6.3 Training programme

Both CON and EXP performed four sets of four repetitions in the deep squat with at least three minutes of rest between sets. The starting load was calculated as approximately 80% of 1RM of the best try during the tests but was adjusted so that the subjects were able to perform all sets with proper technique and observable fatigue. The subjects performed the same number of sets and repetitions in the barbell bench press and a supinated-grip chin-up. EXP performed six sets of four repetitions with at least three minutes rest between sets in the standing calf-raise in a Smith machine apparatus, which only allowed vertical movement of the barbell. The participants placed their forefoot on a heavy brick of approximately 12cm height to ensure enough room to allow deep dorsiflexion during the eccentric part of the lift. In contrast, CON performed six sets of four repetitions with at least three minutes rest between sets in the standing barbell overhead press. This exercise ensured not only to match the number of sets and repetitions of EXP but also to engage the muscles stabilising the knees, hips and spine, which experience heavy loading during the SCR. A whole RT session lasted at least 60 to 75 minutes.

TABLE 3. Training programme of the experimental group.

	Sets	Repetitions	Rest (min)
Squat	4	4	3+
Bench press	4	4	3+
Chin-Up	4	4	3+
SCR	6	4	3+

SCR, standing calf raise

TABLE 4. Training programme of the control group.

	Sets	Repetitions	Rest (min)
Squat	4	4	3+
Bench press	4	4	3+
Chin-Up	4	4	3+
OHP	6	4	3+

OHP, overhead press.

The aerobic endurance training sessions consisted of four to six medium intensity intervals of four to six minutes with two to four minutes of active rest between intervals. A whole session lasted approximately 45 minutes. The 90-minute floorball training followed these sessions and included several episodes of high-intensity running and short bursts of sprinting. The speed sessions comprised four sets of six repetitions with two to three minutes of rest between sets for the CMJ, SJ and DJ followed by three repetitions of 30m sprint from a standing start with at least five minutes of rest between sprints. Lastly, the participants performed three sets of three repetitions of the SLJ with two to three minutes rest between sets. The warm-up included some light jogging, hopping exercises, knee lifts and heel lifts. A whole speed session lasted approximately 75 minutes.

TABLE 5. Training programme of speed session.

	Sets	Repetitions	Rest (min)
CMJ	4	6	2-3
SJ	4	6	2-3
DJ	4	6	2-3
30m sprint	3	1	5+
SLJ	3	3	2-3

CMJ, countermovement jump; SJ, squat jump; DJ, drop jump; SLJ, standing long jump.

6.4 Testing of the 1RM in the deep squat

A Smith machine apparatus (Kraftwerk, Tuusula, Finland), which only allows vertical movement of the barbell served as a testing device. The participants followed the instruction to place the bar across the shoulders, and squat down so that the top surface of the legs at the hip joint was lower than the top surface of the knees and recover into a fully erect position (IPF 2018, 17). The warm-up included a set of ten repetitions with no extra load on the bar, a set of five repetitions at light load and a set of three repetitions at higher loads. Each subject performed at least 5 trials of one repetition with at least five minutes of rest between trials and increasing loads until the subject failed the lift by not reaching sufficient depth or not recovering to a fully erect position. Pick and Becque (2000) reported a coefficient of reliability of $r = 0.997$ for trained and $r = 0.991$ ($p < 0.05$) for untrained populations.

6.5 Testing of the 1RM in the SCR

To test the 1RM in the SCR, subjects placed themselves in the same Smith machine apparatus (Kraftwerk, Tuusula, Finland) as during the squat test. They placed the bar across their shoulders and placed the forefoot on a wooden block of approximately 8cm height. From the neutral position, subjects had to lower the bar 4cm and raise the bar by approximately 8cm so that the end position was 4cm above neutral (Möck et al. 2018). An indicator showed the vertical travel of the bar on a tape measure attached to the apparatus, which allowed visual control of the distance. One researcher focussed only on the vertical travel of the bar, while another ensured safety and controlled that the lift was performed by flexion of the ankles and not extension of the knees or hips. Möck et al. (2018) reported a coefficient of reliability of $r = 0.987$ ($p < 0.01$) for their testing procedure, which included opto-electronic measuring of the bar travel.

6.6 Testing of sprint performance

The subjects warmed up individually before the first trial. At least three trials with at least five minutes of rest were performed and more trials were performed if the times still improved further. The test was conducted in a designated athletics hall (Hipposhalli, Jyväskylä), which had photocells installed at the start line, after 20m and after 30m. The 0-30m time and 0-20m split time was displayed and visible to the participants after each run and 20-30m was calculated from these values. Further, photocells connected to a microcomputer (University of Jyväskylä) served to measure 5-10m and 10-15m split times. The subjects started the runs 50cm before the starting line from a standing position to avoid starting of the timing by their extremities. Concluding from high intraclass correlation coefficients (ICC) of 0.89 to 0.95 for short-distance sprinting, Moir et al. (2004) found that this measurement is reliable and does not require familiarisation.

6.7 Testing of vertical and horizontal jump performance

The researchers used an infrared-based light barrier (University of Jyväskylä) to measure the flight time of the SJ, CMJ and DJ and the ground contact time of the DJ. Sillanpää et al. (1995) validated this system. The following equation allows determination of the jump height (H) given the flight time (T).

$$\mathrm{H} = \frac{1}{8} \times g \times \mathrm{T}^2$$

While the SJ starts from approximately 90° knee flexion and purely concentric movement into full extension, the CMJ starts from a fully erect position followed by a countermovement to approximately 90° knee flexion and subsequent extension of knees, hips and ankles. For the DJ, subjects stepped onto box of 40cm height, took a step off the box to land with both feet in parallel and pushed themselves off the floor as fast and as high as possible. The trial counted when the ground contact time was 220ms or lower. Since jump height (H) in centimeters and ground contact time (GCT) in seconds determine performance in the SJ, the Reactive Strength Index (RSI) (Young 1995) is calculated using the following equation:

$$\mathrm{RSI} = \frac{\mathrm{H}}{\mathrm{GCT}}$$

During all jumps, the subjects had to place their hands on the hips to minimize differences in technique and arm swing. At least three trials with at least one minute of rest between jumps were performed for each jump and more trials were included if performance still increased from jump to jump. Markovic et al. (2004) reported coefficients of reliability of $r = 0.97$ for the SJ and $r = 0.98$ ($p < 0.05$) for the CMJ. Barr and Nolte (2011) published high ICCs of 0.95 for the jump height and 0.92 for the RSI of the DJ. For the SLJ, subjects had to start from a fully erect position and had to jump as far as possible with no further restrictions regarding their technique. The subjects covered the heels of their shoes in loose chalk and the distance from the starting site to the site of impact indicated by the chalk mark was measured using a tape measure. Markovic et al. (2004) found a high ICC of 0.95 for the SLJ.

6.8 Statistical analysis

All parameters tested for normal distribution using the Shapiro-Wilk test. A p-value below 0.05 indicated a significant deviation from the normal distribution. Repeated measures ANOVA allowed the identification of significant differences within groups between the two time points as well as between groups. Prior to the ANOVA, the results were tested for sphericity using Mauchly's W and equality of variances using Levene's test. If the samples did not meet the requirement for parametric testing, the Kruskal-Wallis test substituted the ANOVA. An independent-samples t-test identified potential differences between the two groups at the start of the intervention.

7 RESULTS

7.1 Results of the pre-testing

Tables 6 and 7 present anthropometrical data and the results of the performance tests as described in chapter 6. The groups did not differ significantly in any of the tested parameters.

TABLE 6. Anthropometrical data and performance results of the experimental group prior to the intervention.

	N	Mean	SD	Min	Max
Age (years)	11	17.2	1.5	15	20
Height (m)	11	1.79	0.06	1.69	1.87
Mass (kg)	11	73.7	13.0	59.6	104.6
Squat (kg)	11	101	18.5	75	132.5
RELSQ (kg/kg)	11	1.4	0.3	1.1	1.8
SCR (kg)	11	183.6	26.0	150	230
RELSCR (kg/kg)	11	2.5	0.4	1.9	3.2
0-30m sprint(s)	11	4.27	0.18	3.98	4.55
0-20m sprint (s)	11	3.06	0.13	2.86	3.26
5-10m sprint (s)	11	0.72	0.05	0.63	0.78
10-15m sprint(s)	11	0.65	0.04	0.59	0.70
20-30m sprint (s)	11	1.20	0.05	1.10	1.29
SJ (m)	11	0.32	0.04	0.26	0.41
CMJ (m)	11	0.34	0.05	0.28	0.46
SLJ (m)	11	2.53	0.13	2.35	2.75
DJ (m)	11	0.29	0.07	0.21	0.40
DJ GCT (ms)	11	173	22	147	223
RSI	11	155	38	108	217

SD, standard deviation; Min, minimum; Max, maximum; RELSQ squat/body mass; SCR, standing calf raise; RELSCR SCR/body mass; SJ, squat jump; CMJ, countermovement jump; SLJ, standing long jump; DJ, drop jump; DJ GCT, drop jump ground contact time; RSI, reactive strength index

TABLE 7. Anthropometrical data and performance results of the control group prior to the intervention.

	N	Mean	SD	Min	Max
Age (years)	10	17.1	1.7	15	20
Height (m)	10	1.80	0.08	1.68	1.94
Mass (kg)	10	68.0	11.5	62.3	95.0
Squat (kg)	10	86.6	20.0	70.0	130
RELSQ (kg/kg)	10	1.3	0.2	1.0	1.4
SCR (kg)	10	186.5	35.5	150	270
RELSCR (kg/kg)	10	2.5	0.3	2.1	2.9
0-30m sprint (s)	10	4.30	0.12	4.05	4.44
0-20m sprint (s)	10	3.09	0.08	2.91	3.19
5-10m sprint (s)	10	0.73	0.02	0.67	0.76
10-15m sprint (s)	10	0.66	0.02	0.61	0.69
20-30m sprint (s)	10	1.21	0.04	1.14	1.25
SJ (m)	10	0.32	0.04	0.29	0.40
CMJ (m)	10	0.35	0.03	0.30	0.41
DJ (m)	10	0.28	0.03	0.24	0.34
SLJ (m)	10	2.54	0.14	2.36	2.81
DJ GCT (ms)	10	177	24.82	134	218
RSI	10	153	19	136	183

SD, standard deviation; Min, minimum; Max, maximum; RELSQ squat/body mass; SCR, standing calf raise; RELSCR SCR/body mass; SJ, squat jump; CMJ, countermovement jump; SLJ, standing long jump; DJ, drop jump; DJ GCT, drop jump ground contact time; RSI, reactive strength index

7.2 Changes in squat 1RM and relative squat 1RM

The experimental group increased their mean squat 1RM from 106.1 kg to 119.7 kg while the control group increased their mean 1RM from 101.8 kg to 119.6 kg. These increases translate to relative increases of 13.1% in the experimental group and 17.6% in the control group. The Shapiro-Wilk test confirmed normal distribution, Mauchly's W confirmed sphericity and Levene's test confirmed equality of variances. The analysis of variance (ANOVA) for repeated measures indicated a highly significant effect for the factor repeated measure ($F = 84.731$; $p < 0.001$; $\eta_p^2 = 0.858$) but not for the factor group ($F = 1.543$; $p = 0.235$; $\eta_p^2 = 0.099$).

TABLE 8. Changes in 1RM of the squat after the intervention.

	N	T1 (kg)	T2 (kg)	Relative change (%)	Group difference
EXP	9	106.1 ± 16.8	119.7 ± 17.4	13.1 ± 4.3***	Ns
CON	7	101.8 ± 20.0	119.6 ± 25.00	17.6 ± 9.9***	

Values are presented as means ± standard deviation. *** $p < 0.001$; ns, not significant; EXP, experimental group; CON, control group.

Comparing the results from the individual subjects, it is obvious that the differences between the experimental group are smaller than in the control group. One subject of the control group (ID12) increased his 1RM in the squat to a larger extent than the rest.

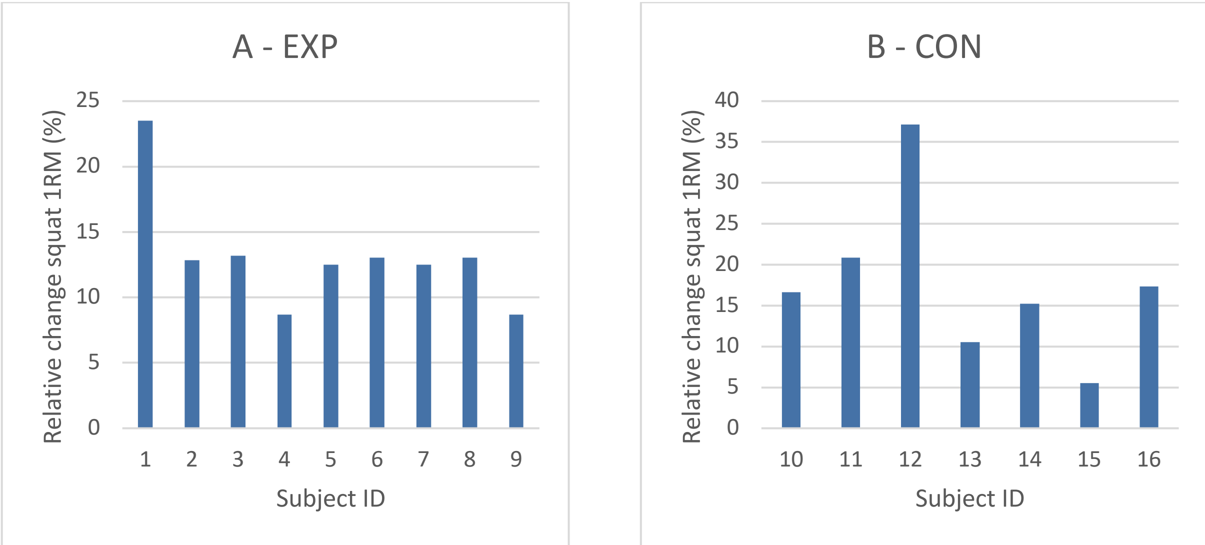

FIGURE 2A, 2B. Relative changes (%) of the 1RM in the squat for the experimental (A) and the control (B) group.

The experimental group increased their mean relative squat 1RM from 1.4 to 1.6 while the control group increased their mean relative squat 1RM from 1.3 to 1.5. These increases translate to relative increases of 11.8% in the experimental group and 14.8% in the control group. The Shapiro-Wilk test confirmed normal distribution, Mauchly's W confirmed sphericity and Levene's test confirmed equality of variances. The analysis of variance (ANOVA) for repeated measures indicated a highly significant effect for the factor repeated measure ($F = 62.485$; $p < 0.001$; $\eta_p^2 = 0.817$) but not for the factor group ($F = 0.505$; $p = 0.489$; $\eta_p^2 = 0.035$).

TABLE 9. Changes in relative 1RM of the squat after the intervention.

	N	T1 (kg/kg)	T2 (kg/kg)	Relative change (%)	Group difference
EXP	9	1.4 ± 0.3	1.6 ± 0.3	11.8 ± 4.9***	
CON	7	1.3 ± 0.4	1.5 ± 0.4	14.8 ± 9.1***	Ns

Values are presented as means ± standard deviation. *** p < 0.001; ns, not significant; EXP, experimental group; CON, control group.

7.3 Changes in SCR 1RM

The experimental group increased their mean SCR 1RM from 186.7 kg to 216.4 kg while the control group increased their mean 1RM from 193.6 kg to 224.3 kg. These increases translate to relative increases of 16.6% in the experimental group and 17.2% in the control group. The Shapiro-Wilk test confirmed normal distribution, Mauchly's W confirmed sphericity and Levene's test confirmed equality of variances. The analysis of variance (ANOVA) for repeated measures indicated a highly significant effect for the factor repeated measure ($F = 57.088$; $p < 0.001$; $\eta_p^2 = 0.803$) but not for the factor group ($F = 0.015$; $p = 0.903$; $\eta_p^2 = 0.001$).

TABLE 10. Changes in 1RM of the SCR after the intervention.

	N	T1 (kg)	T2 (kg)	Relative change (%)	Group difference
EXP	9	186.7 ± 28	216.4 ± 25.8	16.6 ± 7.5***	Ns
CON	7	193.6 ± 39.9	224.3 ± 37.7	17.2 ± 13.7***	

Values are presented as means ± standard deviation. *** $p < 0.001$; ns, not significant; EXP, experimental group; CON, control group.

These results suggest accepting Hypothesis 1, although the control group improved their 1RM to similar extent. In the experimental group, only one subject (ID7) increased his 1RM in the SCR to small extent but the majority increased their 1RM to about 10% or more. In the control group, four out of seven subjects (ID13; ID14; ID15; ID16) increased their 1RM to about 10%

or less but the remaining three subjects (ID10; ID11; ID12) increased their 1RM to a large extent. For this parameter, as well as for the squat 1RM, subject ID12 increased his 1RM the most.

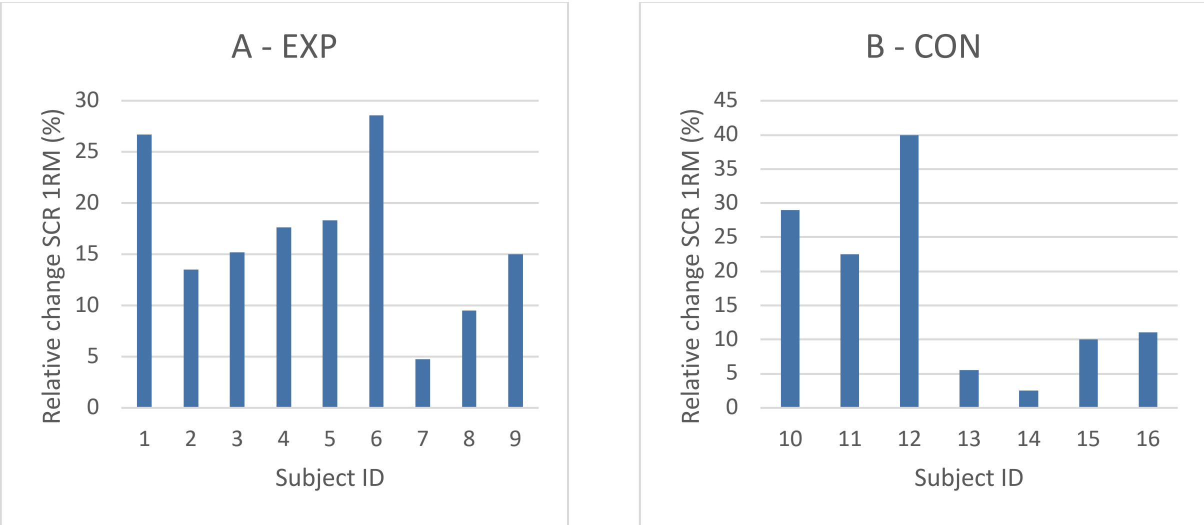

FIGURE 3A, 3B. Relative changes (%) of the 1RM in the SCR for the experimental (A) and the control (B) group.

Both groups increased their SCR 1RM normalised to their body mass. The experimental group increased their SCR 1RM by 15.2% (2.5 → 2.8) and the control group increased their SCR 1RM by 14.3% (2.5 → 2.8). Meeting the assumptions for parametric testing, the ANOVA revealed a significant result for the factor repeated measure ($F = 42.305$; $p < 0.001$; $\eta_p^2 = 0.751$) but not for the factor group ($F = 0.080$; $p = 0.782$; $\eta_p^2 = 0.006$).

TABLE 11. Changes in relative 1RM of the SCR after the intervention.

	N	T1 (kg/kg)	T2 (kg/kg)	Relative change (%)	Group difference
EXP	9	2.5 ± 0.4	2.9 ± 0.4	15.2 ± 7.0***	
CON	7	2.5 ± 0.3	2.8 ± 0.3	14.3 ± 12.2***	Ns

Values are presented as means ± standard deviation. *** p < 0.001; ns, not significant; EXP, experimental group; CON, control group.

7.4 Changes in sprint performance

The statistical analysis of the sprint parameters did not reveal any significant results for the factor repeated measure or the factor group. In cases where the sample deviated significantly from normality, the Kruskall-Wallis test substituted the ANOVA. These results suggest rejecting Hypothesis 2.

TABLE 12. Changes in all sprint measures after the intervention.

	N	T1	T2	Relative change (%)
0-30m sprint EXP	9	4.27 ± 0.21	4.28 ± 0.18	0.3 ± 1.8
0-30m sprint CON	7	4.29 ± 0.12	4.27 ± 0.11	-0.4 ± 1.9
0-20m sprint EXP	9	3.06 ± 0.14	3.07 ± 0.13	0.4 ± 1.7
0-20m sprint CON	7	3.08 ± 0.10	3.06 ± 0.08	-0.6 ± 1.9
20-30m sprint EXP	9	1.20 ± 0.06	1.20 ± 0.06	-0.2 ± 1.7
20-30m sprint CON	7	1.21 ± 0.04	1.20 ± 0.04	-0.9 ± 1.3
5-10m sprint EXP	9	0.72 ± 0.05	0.72 ± 0.04	1.0 ± 2.9
5-10m sprint CON	7	0.73 ± 0.03	0.726 ± 0.02	0.1 ± 3.2
10-15m sprint EXP	9	0.65 ± 0.04	0.65 ± 0.04	-0.6 ± 4.4
10-15m sprint CON	7	0.66 ± 0.03	0.65 ± 0.02	-1.5 ± 2.7

Values are presented as means ± standard deviation; EXP, experimental group; CON, control group.

The individual data indicates that six out of nine subjects of the experimental group and five out of seven of the control group improved their performance in the sprint up to 30m. This improvement was not significant. In the experimental group, two subjects (ID3; ID4) increased their sprint time by more than two percent, which is also the case for one subject of the control group (ID12). Subjects ID3 and ID12 also increased their body mass by 6.8% and 4.9%.

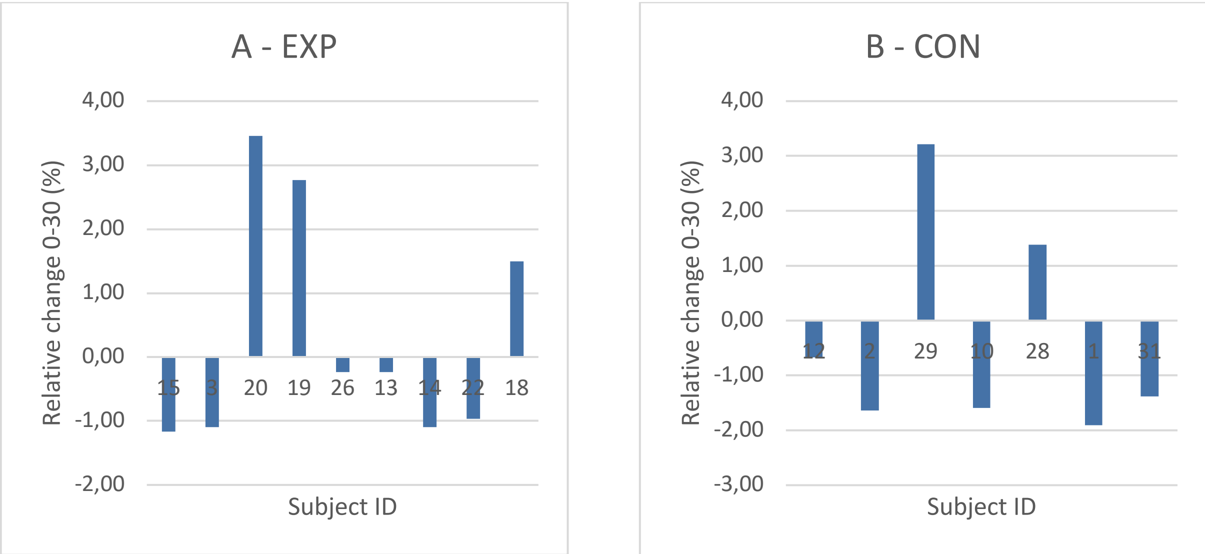

FIGURE 4A, B. Relative changes (%) of 0-30m sprint time for the experimental (A) and the control (B) group.

For the parameter 0-20m sprint time, the individual results are similar to those of the parameter 0-30m sprint time. The same subjects, which decreased their performance over 20m, decreased their performance on the first 20m by at least three percent. For both parameters, subject ID1 increased his performance the most.

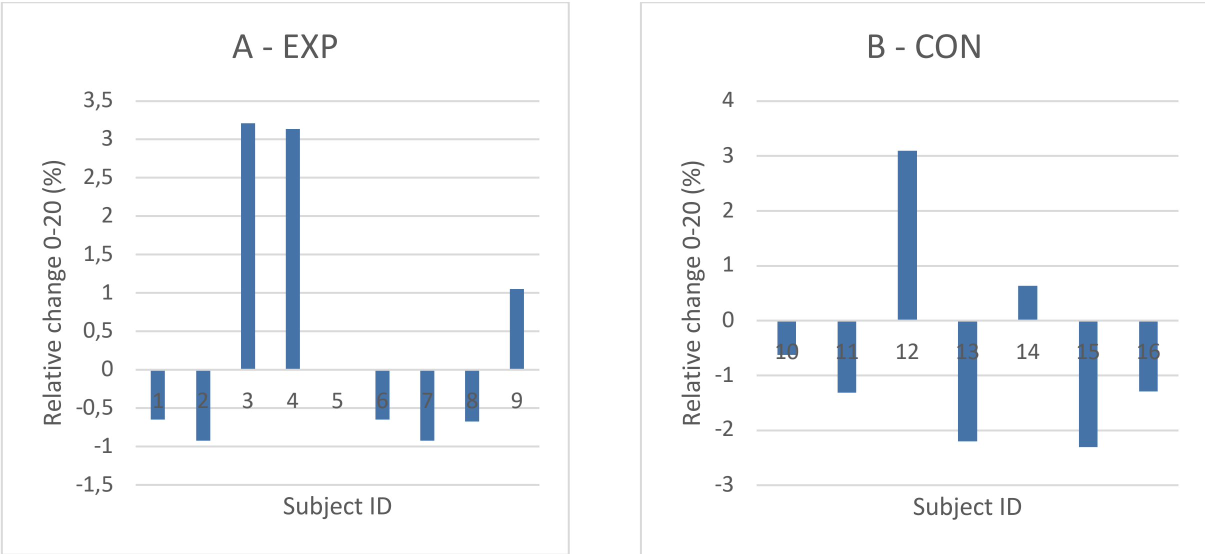

FIGURE 5A, 5B. Relative changes (%) of 0-20m sprint time for the experimental (A) and the control (B) group.

7.5 Changes in vertical and horizontal jump performance

The statistical analysis of the jump parameters did not reveal any significant results for the factor repeated measure or the factor group. In cases where the sample deviated significantly from normality, the Kruskall-Wallis test substituted the ANOVA. These results suggest rejecting Hypothesis 3.

TABLE 13. Changes in vertical and horizontal jumps after the intervention.

	N	T1	T2	Relative change (%)
SJ EXP	9	0.32 ± 0.05	0.33 ± 0.03	5.1 ± 8.5
SJ CON	7	0.31 ± 0.12	0.32 ± 0.04	3.81 ± 8.3
CMJ EXP	9	0.35 ± 0.06	0.35 ± 0.04	0.7 ± 5.9
CMJ CON	7	0.35 ± 0.03	0.34 ± 0.04	-2.6 ± 5.0
SLJ EXP	9	2.53 ± 0.13	2.55 ± 0.16	-0.2 ± 2.5
SLJ CON	7	2.54 ± 0.14	2.55 ± 0.18	0.4 ± 3.7
DJ EXP	9	0.29 ± 0.07	0.26 ± 0.03	-8.6 ± 16.0
DJ CON	7	0.28 ± 0.02	0.26 ± 0.05	-8.3 ± 18.6
GCT EXP	9	170 ± 14	168 ± 14	-0.3 ± 11.2
GCT CON	7	184 ± 23	174 ± 14	-4.5 ± 13.0
RSI EXP	9	159 ± 38	144 ± 17	-6.0 ± 19.6
RSI CON	7	151 ± 19	137 ± 26	-8.4 ± 21.7

Values are presented as means ± standard deviation; SJ, squat jump; CMJ, countermovement jump; SLJ, standing long jump; DJ, drop jump; DJ GCT, drop jump ground contact time; RSI, reactive strength index; EXP, experimental group; CON, control group.

The individual results for the SJ indicate that seven out of nine subjects of the experimental group increased their jump height in the squat jump, whereas only two of the control group increased their jump height. One subject (ID9) of the experimental group experienced the largest decrease in jump height of more than ten percent. This subject presented with the highest SJ of 0.41m prior to the intervention.

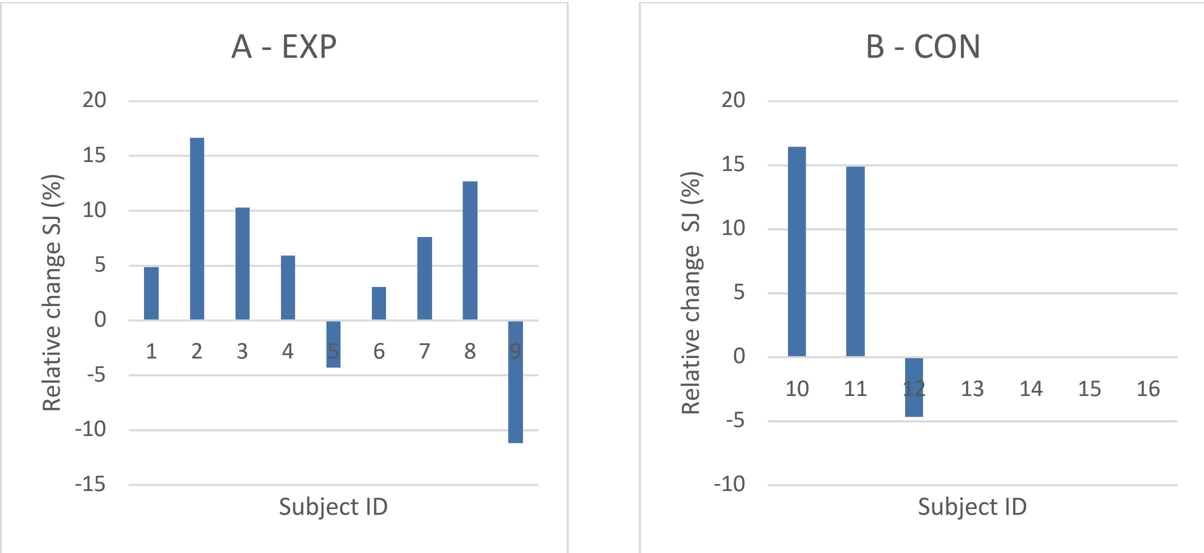

FIGURE 6A, 6B. Relative changes (%) of the SJ height for the experimental (A) and the control (B) group.

In the experimental group, four out of nine subjects decreased their performance in the SLJ, which was the case for only two subjects of the control group. The largest increase (+4.2%) was achieved by subject ID13 in the control group but also the largest decrease was seen in the control group (ID12; -6,5%).

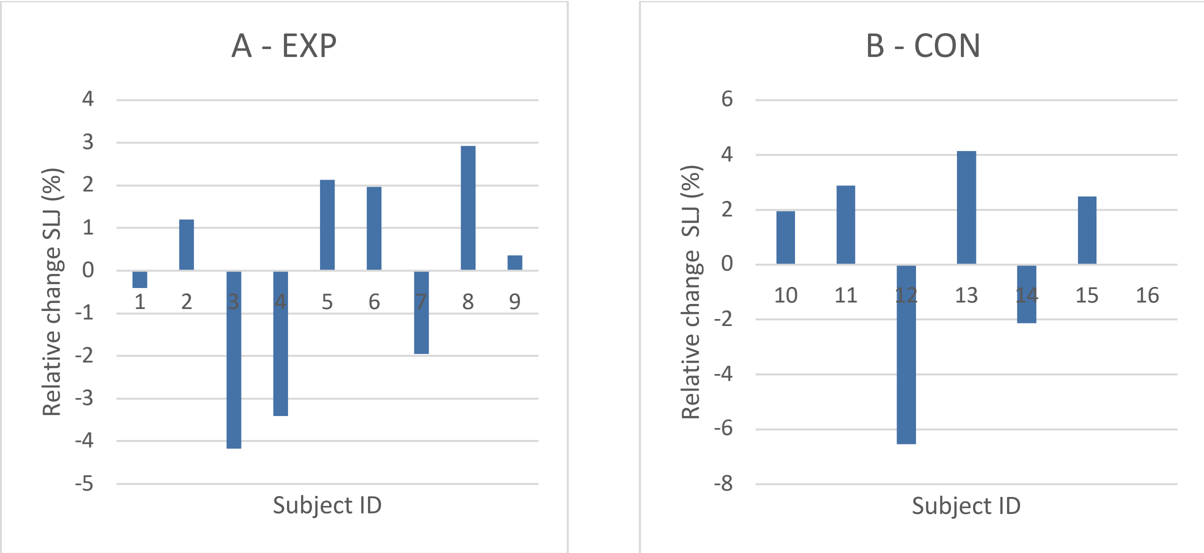

FIGURE 7A, 7B. Relative changes (%) of the SLJ height for the experimental (A) and the control (B) group.

Two subjects of the experimental group exhibited decreases in SLJ performance, whereas four subjects of the control decreased their performance and one maintained his performance. The largest increase was seen in the experimental group by subject ID5.

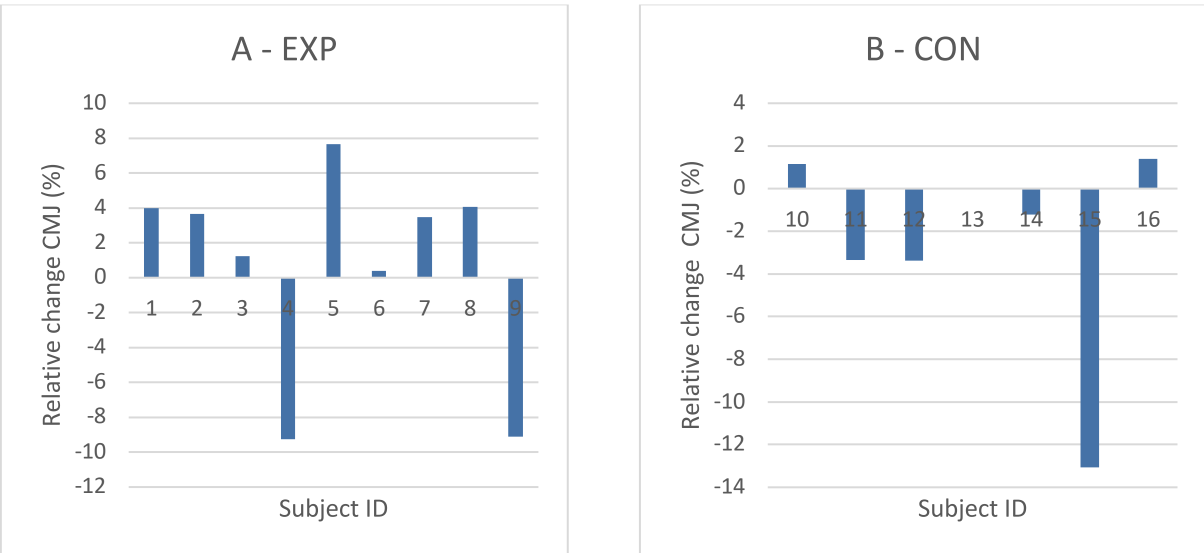

FIGURE 8A, 8B. Relative changes (%) of the CMJ height for the experimental (A) and the control (B) group.

The majority of subjects across both groups decreased their jump height in the DJ with the largest decreases occurring in the experimental group (ID4, -30%; ID5, -27.0%). Subject ID31 of the control group increased his jump height the most by 24.1%. One subject of the experimental group (ID2) did not change his performance at all while another subject (ID8) increased his jump height only marginally (+3.3%).

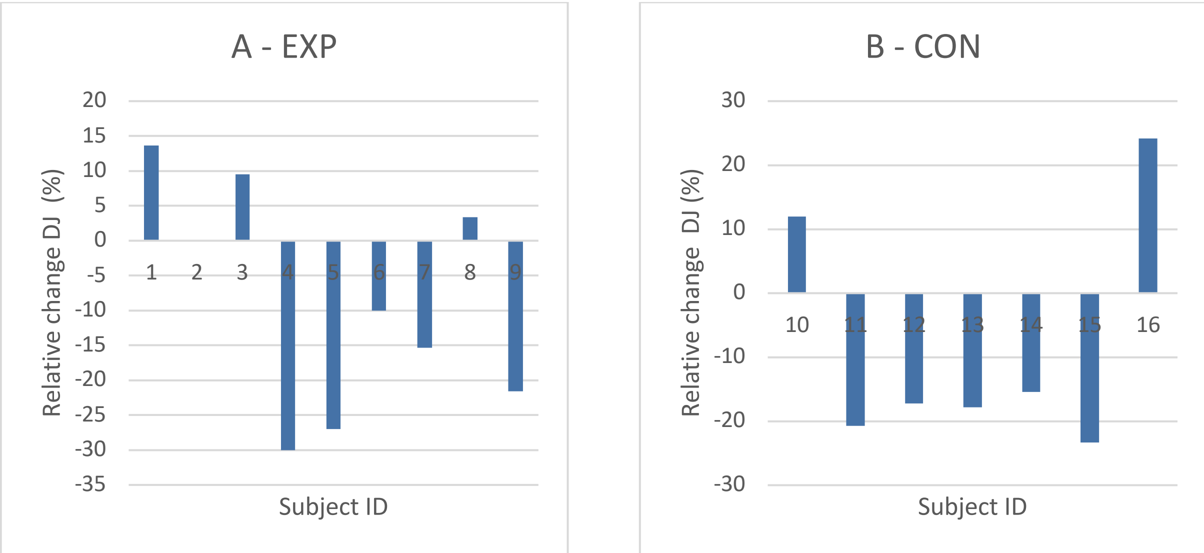

FIGURE 9A, 9B. Relative changes (%) of the DJ height for the experimental (A) and the control (B) group.

7.6 Changes in training loads

The training loads for the squat and SCR in the first sessions were calculated as approximately 80% of the 1RM of each lift. Whilst all subjects succeeded at performing four sets of four repetitions of the squat at 80% of their 1RM, three out of nine subjects in the experimental group were unable to perform several repetitions at 80% of their 1RM in the SCR. This resulted in a mean starting intensity of 75.7%. All subjects but one (ID3) increased their training load by a mean of 23%. The subject ID3 reported back pain during the SCR and squat, therefore, the training loads were drastically decreased until the subject reported full recovery. Despite the lack progressive load, this subject increased his SCR 1RM by 15.2% and his squat 1RM by 13.2%.

One subject (ID15) of the control group failed to increase his training loads in the squat and increased his 1RM only by 5.6%, which presents the smallest increase in 1RM among all subjects. All other subjects increased their training loads by 20.3% on average. In the last training session, the subjects performed four sets of four repetitions at 80.1% on average. This is similar to an average intensity of 78.1% in the experimental group for the SCR in the last training session.

8 DISCUSSION

In comparison to population data from the literature, the data from the population of this study seems relatively homogenous with few exemptions. The mean values of the squat in relation to body mass would suggest that the majority of subjects were moderately trained at the start of the intervention, while the results of the sprint tests indicate a good performance level. The subjects in the study by Möck et al. (2018) performed the 1RM in the SCR at a mean 191.91kg, which is 2,57-times their body mass on average. The subjects of this study performed slightly worse on these parameters suggesting that their level of plantar flexion strength is lower than that for the sprints compared to population means. The results of the vertical jump tests appear surprisingly poor, which is not the case for the SLJ. Considering the lowest values reported of some parameters, a few subjects of this study must be regarded untrained. This is well in line with the training history documented from these subjects. This in contrast to the best values seen for these parameters, which suggest relatively high level of performance. These were the results of subjects following systematic RT for at least six months or longer. In conclusion, the results at the beginning of the intervention support a reasonable expectation that at least some of the subjects improved their performance after six weeks of heavy RT.

The most consistent improvements were seen for the 1RM in the squat and in the SCR. Both groups significantly improved their 1RM in the squat by 13.1% (EXP) and 17.6% (CON). While most subjects in the experimental group increased their 1RM load between 8.7% and 13.2%, subject ID1 showed the largest increase of 23.5%. This larger increase can be partially explained by the training status of this subject prior to the intervention. The squat in relation to body mass (RELSQ) reflects the training status and was at 1.1kg/kg, which was the second-lowest value of all subjects. The individual changes in the control group show higher variance as indicated by the smallest increase of 5.6% (ID15) and overall largest increase of 37.1% (ID12). Subject ID1 experienced constant technique issues with the squat exercise throughout the intervention, which suggests that flawless execution of a deep squat is a requirement to maximise adaptations in the given exercise. One should consider several aspects when interpreting the dramatic increase of subject ID12 of 37.1%. Firstly, this subject had little to no experience in the deep squat, therefore, one would expect large improvements. Secondly, the lack of experience might limit the subject's courage to perform a deep squat with an accustomed weight placed on his shoulders. This would lead to underestimation of the subject's maximal strength potential.

The changes in the SCR 1RM are more pronounced in both groups but contrary to expectations, the control group increased their 1RM to a higher degree on average. One subject of the experimental group (ID7) increased his 1RM by only 4.8%, while the average increase was 16.6% in this group. This particular subject presented with an initially high 1RM relative to his body mass (RELSCR) of 2.7kg/kg, which would partially explain smaller increase. However, other subjects, especially ID9, who started with the highest RELSCR of 3.2kg/kg, still managed to increase their 1RM to a similar extent as the rest of the group. Like for the squat, subject ID15 increased his SCR 1RM to a higher degree than most other subjects. This subject also started with the lowest RELSCR of all participants, which is in support of the idea that a lower training status allows for larger improvements and vice versa. Despite not performing the SCR exercise throughout the intervention, three subjects of the control group ID10; ID11; ID12) increased their 1RM by more than 20%. As for the squat 1RM, subject ID29 increased his 1RM the most (+40%). Considering the size of this group (n = 7), one would have to admit that the result of ID12 had a large impact on the group mean, which makes the results seem like the control group increased their 1RM to a higher extent as the experimental group. Nevertheless, two subjects in this group (ID10; ID11) also increased their 1RM to higher extent as the average of the experimental group. To summarise, these results suggest that performing the SCR exercise over six weeks does induce increases in 1RM significantly different from not performing this specific exercise. This not only raises the question whether this test is valid in regard of the maximal strength of plantarflexors but also whether other factors determine the performance in this test.

Throughout the testing procedure it became obvious that many subjects struggled to main a certain level of hip and knee extension. Since the majority of subjects performed lifts at loads beyond 200kg, one can imagine that these loads cause discomfort in the lumbar spine as reported by Pallarés et al. (2019, 9). These factors can possibly interfere with the subjects' motivation to perform the lift but also hinder them from fully activating the plantar flexion. This is supported by the fact that some subjects had to reduce the training load below the estimated 80%, which resulted in a mean starting load of 75.7% in the experimental group. If one considers the strength of the hip and knee extensors and extensors of the spine to be limiting factors in the SCR, increases thereof could explain the improvements in the control group. In fact, the relative change in the squat, which is an exercise to develop the aforementioned muscle groups, correlated quite well with the relative change in the SCR ($r = 0.687$; $p = 0.003$). This seems to be especially the case for subject ID12, who increased his squat 1RM by 37.1% and his SCR 1RM by 40% without performing this exercise during the intervention. High correlations between the squat 1RM and the SCR 1RM prior to ($r = 0.760$; $p < 0.001$) and even more after the intervention ($r = 0.794$; $p < 0.001$) further support this notion.

Morphological and neural factors determine the force-generating capacity of an individual. The body of evidence implies that neural adaptations, depicted as increases is recruitment and innervation frequency, predominate morphological adaptations in the first few weeks of training (Häkkinen & Komi 1983; Narici et al. 1989; Aagaard et al. 2002a, 2002b; Del Vecchio et al. 2018). However, a number of studies report morphological adaptations after only six weeks of training (Luethi et al. 1986; Bell et al. 1991; Abe et al. 2000), while others did not find changes in twitch properties (Van Cutsem et al. 1998; Nuzzo et al. 2017). In conclusion, the changes in squat and SCR 1RM seen here are within the expected range (Ahtiainen et al.2016). Higher changes in the SCR are likely to be explained by the fact that the majority of subjects had at least six months of experience in the squat but no subject had experience in the SCR. Morphological changes possibly contribute to these changes but it appears reasonable to assume that neural adaptations caused these short-term effects.

The mean changes in all measures of the short-distance sprint were only marginal with some of them improving and others declining. None of these changes were significant. Considering the individual results of the 30m sprint time, the results of six subjects show a trend of improvement. The improvements were between -0.2% and -1.2%, which is close to the improvements reported by Styles et al. (2016) for the 20m sprint time after six weeks of training. On the other hand, two subjects (ID3; ID4) were substantially slower after the intervention (+3.5%; +2.8%). Several factors can potentially explain these results. Subject ID3, whose performance decline was the largest, reported pain and discomfort in the back during the intervention. These circumstances prohibited load progression during the intervention, although he could increase his 1RM in both exercises. Additionally, this subject increased his body mass by 3.7kg (3.5%), which requires higher force generation to accelerate quickly. In the case of subject ID19, it seems reasonable to assume that the subject was slightly fatigued at the time of the measurement. Despite repeated announcement, two subjects did not follow the instruction to rest at least 48 hours before the tests. Their moderate increase in the squat 1RM likely reflects this fatigue. The same notions apply to the results for the 20m sprint time.

A similar pattern appears in the control group where five out of seven subjects improved their 30m time to a similar extent as the experimental group. Surprisingly, subject ID12, who increased his 1RM in both exercises by about 40%, decrease his performance in the sprint by 3.2%. One possible explanation is the concomitant increase in body mass by 3kg (4.8%). It seems reasonable to believe that increases in body mass affect motor tasks requiring high velocities more than maximal strength tests. In contrast to this are the results of subject ID2, which indicate improved 20m and 30m sprint times despite a body mass increase of 6.8%. Taking the initial performance levels of these two subjects into account, it becomes obvious that subject ID12 was among the fastest of all subjects (fastest in the control group), whereas subject ID11 was only average. This supports the common observation that highly trained individuals are less likely to improve. The results here are in line with the literature, which indicates only marginal if at all significant improvements in short-distance sprinting (McBride et al. 2002; Blazevich & Jenkins 2002; Moir et al. 2007; Styles et al. 2006; Rumpf et al. 2016).

The experimental group increased their jump height in the SJ by 5.1% and the control group by 3.8% but these changes were not significant. Most subjects of the experimental group increased their jump height by 3.1% to 16.6% but two subjects (ID5; ID9) decreased their jump height by 4.3% and 11.2%. The decrease of 4.3% by subject ID5 is only small but it is unclear why this subject failed to increase is jump height, since he improved his 1RM in both tests substantially. This result is contrast to a 7.7% increase in the CMJ. As stated above, one subject failed to follow the instructed rest period of at least 48 hours before testing, which likely explains a dramatic decrease in jump height in the SJ and in the CMJ. Interestingly, only two subjects of the control group increased their jump, whereas the other subjects showed no change or a decrease in jump height. A similar pattern occurs in the results of the CMJ but the improvements are smaller. Like in the sprint tests, two subjects substantially decreased their performance, potentially induced by fatigue. The largest decrease was seen in subject ID15 (-13.1%), which is contrast to this subject's improvement in 20m and 30m sprint times. According to literature, gains in maximal strength transfer well to vertical jump performance (Adams et al. 1992; Augustsson et al. 1998; Channell & Barfield 2008; Hartmann et al. 2012; Anderst, et al. 1994; Fatourus et al. 2000), which is in contrast to the results of this study. Firstly, one might argue that the weekly volume of jump training was insufficient to allow transfer of maximal strength to motor tasks restricted to shorter time periods. Secondly, it seems hard to completely rule out a certain amount of fatigue accumulated over this training period. If the latter was the case, it would mean that highly dynamic motor tasks involving a SSC (SJ is purely concentric) are more sensitive to fatigue than maximal strength measurements.

The results are more diverse for the SLJ but mean changes of -0.2 (EXP) and 0.4 (CON) were not significant. In the experimental group, four subjects exhibited a performance decrease, while only two subjects of the control group decreased their performance and one remained unchanged. The nature of the SLJ prohibits standardised technique as possible for the vertical jumps assessed here. Therefore, fluctuations of performance likely reflect within-subject variation in technique than the ability to maximally activate the hip and knee extensors. However, the largest decreases are seen in subjects ID20, ID19 and ID29. As discussed previously, increases in body mass and fatigue potentially contribute to these results.

In contrast to the results of the other vertical jumps, the majority of subjects drastically decreased their jump height in the drop jump. This decrease was the same for both groups, indicating that training of the plantarflexors in the experimental group did not necessarily contribute to this decrease. A concomitant but only marginal decrease in GCT during the DJ can only partially explain the large decreases in jump height. One aspect to consider is that the height subjects jumped from during the intervention was slightly lower than the 40cm box during the tests. In addition, different grounds potentially alter ground reaction forces and subsequently the kinematics and technique of the jump (Ishigawa & Komi 2003). Although theoretical considerations would lead one to expect improved DJ performance after RT of the plantarflexors, the results here did not confirm this. Some studies examining the effects of RT on DJ height did not find improvements in DJ performance (Häkkinen & Komi 1983; Kotzamanidis, Chatzopoulus, Michailidis, Papaiakovou, Patikas 2005).

One major limitation to the interpretation of these results is the uncertainty regarding the participation during the weekly speed sessions. Although the majority of subjects participated in the supervised speed sessions, some showed higher attendance rates than others. When a subject was unable to attend the supervised session, he was instructed to perform the exercise on his own. It is unclear, whether this was always the case. One would assume that concomitant training of the sprints and jumps is a necessity to transfer gains in maximal strength to highly dynamic, complex motor tasks. Several publications support this notion (Faigenbaum et al. 2007; Behringer et al. 2011; Lloyd et al. 2016). The marginal to none existent improvements in the jumps and sprints can also be explained by too low training volumes of these exercises, since they were only performed once per week. Apart from that, it seems reasonable to question if the two aerobic endurance sessions per week interfered with the adaptation to plantar flexion training. Studies examining the effects of concurrent training found that combined strength and endurance training leads to similar improvements in maximal strength compared to RT alone. Interestingly, Mikkola et al. (2011) found that concurrent training blunted increases in RFD, whereas the strength only group increased their RFD. Since RFD is critical in highly dynamic motor tasks, this could partially explain the lack of adaptations of the experimental group in the corresponding tests. In addition, no information on the structure of the floorball sessions is available. It seems reasonable to assume that inter- and intraindividual differences in the activity during these sessions exist. This would result in differences in the total amount of short-distance sprints, which the subjects performed throughout the intervention. On the other hand, one might expect that highly fatiguing floorball sessions affect the quality of the RT and speed sessions and subsequently the adaptation to these stimuli. Another limitation to this study is that the results do not allow any explanation of the mechanisms causing the adaptations or lack thereof. Since the sample size of this subject is very small, statistical analyses should be regarded with caution.

9 CONCLUSION

Heavy RT performed twice weekly over six weeks is sufficient to elicit gains in maximal strength of the knee and hip extensors. These improvements translate only partially to motor tasks requiring a high RFD and power output. Additional weekly training sessions including different jump and sprint exercises were insufficient in supporting the transfer of maximal strength to sprinting. The maximal strength of planter flexion, assessed during a 1RM test in the SCR, was shown to correlate with short-distance sprinting capacity (Möck et al. 2018). This study aimed to examine the effects of additional plantar flexion RT on short-distance sprinting and vertical and horizontal jump performance. The results of this study suggest that athletes do not benefit from performing heavy plantar flexion training when added to a conventional RT programme involving the deep squat. Furthermore, the results of the 1RM tests indicate that additional plantar flexion training does not lead to higher gains in maximal strength of the plantarflexors. One would conclude that other factors such as core stability, hip and knee extension strength present limiting factors when performing high load SCR. This is supported by the fact that improvements in the SCR highly correlated with improvements in the squat across both groups.

A deeper analysis of the individual data points revealed that the absence of improvements co-existed with gains in body mass. These gains in body mass likely masked some improvements, since a higher body mass requires higher forces for fast displacement. Additionally, the training status in the individual parameter influenced the development thereof. Some of the findings of this study lead the author to question, whether all subjects were fully recovered during the testing procedures. In conclusion, heavy RT intervention are a safe and effective method of improving maximal strength of the muscle involved in the tested motor task. If the aim is to develop short-distance sprint performance or jump performance, exercises for these should be performed more than once per week. Careful monitoring of body mass changes and recovery status is warranted when interpreting results of performance tests. Furthermore, it seems worth pointing out that heavy RT twice a week can be performed without negatively affecting sprint performance over six weeks.

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