Go heavy or go home?

In-season heavy load resistance training vs power/plyometric training on muscle size, architecture and strength.

SIMON AUNE

SUPERVISOR
Thomas Bjørnsen
Fredrik Tonstad Vårvik

University of Agder, 2023
Faculty of Health and Sport
Department of Sport Science and Physical Education

Table of Contents

Acknowledgements

Over the past two years, my journey as a master's student has been incredibly rewarding, filled with valuable friendships, knowledge, and unforgettable experiences that will always hold a special place in my heart. I have had the privilege of learning from exceptional lecturers who possess remarkable expertise in their respective fields, and their willingness to share their experiences and expertise with us students has been truly inspiring.

Engaging in a comprehensive research project has provided me with a deep understanding of the dedication and passion required to expand our knowledge in the field of sports science. This period has solidified my drive and ambition to pursue a career in the world of sports.

I would like to express my gratitude to my fellow students, particularly those who were involved in the same project. Your collaboration and support made this journey both amazing and challenging, as we worked tirelessly together to complete this master's thesis. The countless long days and hours we dedicated to this endeavor have truly paid off.

Lastly, I would like to extend my sincerest appreciation to our supervisors, Thomas Bjørnsen and Fredrik Tonstad Vårvik, for their unwavering guidance, valuable feedback, and insightful advice throughout the entire process, right up until the final days. Your expertise and dedication have been invaluable, and I am deeply grateful.

Thank you all for contributing to this chapter of my academic journey.

Simon Aune
Kristiansand, 2023

Sammendrag

Hensikt: Studien undersøkte effektene av tung styrketrening vs power og plyometrisk trening på muskelstørrelse-, arkitektur og styrke hos kvinnelige sub-elite håndballspillere i sesong.

Metode: Trettien deltakere fra to seniorlag ble randomisert til enten en tung styrketrening gruppe (TSG; n=16, 19,5±2,8 år, 169,9±6,2 cm, 70,2±13,9 kg) eller en power/plyometrisk gruppe (PPG; n=15, 20,4±2,8 år, 170,4±5,9 cm, 65,6±6,8 kg). Under 2 økter i uken gjennomførte TSG 2-6 sett med 80-85% av 1RM, mens PPG utførte 2-4 sett med power-øvelser på ≤50% av 1RM og 75-90 plyometriske hopp. Før- og etter en 12 ukers intervensjon ble fettfri masse (FFM) og maksimal styrke estimert av Dual-X-Ray-Absorptiometry, 1RM, isometrisk styrke (MVC) og pneumatisk benpress (Fmax). Muskeltykkelse (MT) og tverrsnittsareal (CSA) ble målt ved ultrasonografi av rectus femoris (RF) og vastus lateralis (VL) på distale, midtre og proksimale områder av låret. Pennasjonsvinkel (PA) og fassikellengde (FL) ble vurdert i midtre del av VL. FFM økte likt i begge gruppene.

Resultater: Forskjell mellom gruppene ble funnet i midtre RF-CSA og midtre VL-MT i favør TSG. PPG økte distal RF-CSA. TSG økte distal VL-MT og midtre VL-MT. Ingen signifikant endring ble funnet i pennasjonsvinkel eller fassikellengde. TSG økte mer i 1RM, men ingen forskjell mellom gruppene ble funnet i Fmax eller MVC. TSG økte i alle styrkemål, mens PPG økte 1RM knebøy og MVC.

Konklusjon: Begge gruppene FFM, men muskelstørrelsen i VL og RF viste regionale og ikke-homogene endringer mellom gruppene med større effekt i TSG. TSG viste også større effekt på maksimal styrke.

Nøkkelord: Styrketrening, håndball, muskelstørrelse, muskelarkitektur, muskelstyrke, kvinnelig, sesong

Abstract

Purpose: This study investigated the effects of in-season heavy-load resistance training vs power and plyometric training on muscle size-, architecture and strength, in female sub-elite handball players.

Methods: Thirty-one participants from two senior teams were randomized into a heavy-load resistance group (HRG; n=16, 19.5±2.8yrs, 169.9±6,2cm, 70.2±13.9kg) or a power/plyometric group (PPG; n=15, 20.4±2.8yrs, 170.4±5.9cm, 65.6±6.8kg). In biweekly sessions HRG performed 2-6 sets at 80-85% 1RM, while PPG performed 2-4 sets of power-exercises at ≤50% 1RM with 75-90 plyometric bodyweight jumps. Pre and post the 12-week intervention, fat-free mass (FFM) and maximal strength were assessed by Dual-X-Ray-Absorptiometry, one repetition maximum (1RM), isometric strength (MVC) and Leg Press pneumatic resistance force (Fmax). Muscle thickness (MT) and cross-sectional area (CSA) were obtained by ultrasonography from rectus femoris (RF) and vastus lateralis (VL) at the distal, middle and proximal thigh region. Pennation angle (PA) and fascicle length (FL) were assessed at VL middle region.

Results:FFM increased similarly in both groups. Between group %change was found in middle RF-CSA and middle VL-MT favouring HRG. PPG increased distal RF-CSA. HRG increased distal VL-MT and middle VL-MT. No change was found on pennation angle or fascicle length. HRG increased more in 1RM, but no between group difference was found in Fmax or MVC. HRG increased all strength measures, while PPG increased 1RM squat and MVC.

Conclusion: Both groups increased FFM, but muscle size of VL and RF showed non-homogenous effects between groups with greater effect in HRG. HRG also showed greater effect on maximal strength.

Keywords: Strength training, handball, muscle size, muscle architecture, muscle strength, female, in-season

Abbreviations

RFD: Rate of force development

CSA: Cross-Sectional Area

SD: Standard Deviation

Cm: Centimetre

Kg: Kilogram

RIR: Repetitions in Reserve

1RM: One-Repetition Maximum

CV: Coefficient of Variation

FFM: Fat-free mass

FV: Force-velocity

MVC: Maximum voluntary contraction

ES: Effects size

DXA: Dual-energy X-ray absorbiometry

Fmax: Peak force

RCT: Randomized controlled trial

Structure of thesis

Part 1: Presents the theoretical background for the study, a methodological chapter of how the study was performed, and a chapter discussing the methodology.

Part 2: Presents a research paper, written following the guidelines from the open access of the Scandinavian Journal of Medicine & Science in Sports. Part 2 consists of an AMA-style manuscript: Introduction, methods, results, discussion, strengths, and limitations of the study, and perspectives.

Part 3: Consists of appendices such as approval, informed consent, and application of ethical approval.

PART 1

THEORETICAL BACKGROUND AND METHODS

Table of content

1 Introduction

An athlete’s ability to produce high amounts of force at different velocities is regarded as a decisive factor for performance in team-sport (Cormier et al., 2021; Suchomel et al., 2016). Depending on the individuals' sport-specific tasks, force has to be generated rapidly, maximally, or repeatedly (Suchomel et al., 2016). This holds especially true for handball, a rigorous contact sport that involves a multitude of fast, intense and dynamic actions, including jumping, sprinting, throwing, and engaging in duels. These activities in handball result in considerable requirements for force production (Chelly et al., 2010; Michalsik & Aagaard, 2014).

A limiting factor and prerequisite for generating force is an athlete’s muscular strength both maximal and explosive, which in turn is strongly determined by the neural system and muscle size (Blazevich et al., 2006; Suchomel et al., 2018). A larger muscle contains more contractile material, giving it more force producing potential, but the muscle fibre type, fascicle length and pennation angle of the contractile fibres will modulate the expression of this force (Blazevich et al., 2006). Muscle fibres attaching with a large pennation angle will have a relatively higher physiological cross-sectional area and shorter fascicle length, and therefore more relative maximal force-production potential at lower velocity, while longer fascicle lengths and smaller pennation angle increases the number of sarcomeres arranged in series being more effective at high velocities.

To enhance force production, handball players have used various training methods in-season, but the effects on muscle architectural characteristics differs based on the training method used (Wagner et al., 2017). Traditionally heavy load low velocity resistance training has been seen as the most effective for increasing structural adaptions such as muscle size compared with lower load high velocity training, and since muscle size is a determining factor for force production, heavy resistance training has therefore been used extensively in team-sport athletes (Arntz et al., 2022; Cormie et al., 2011a; Grgic et al., 2021; Ramirez-Campillo et al., 2022). Power and plyometric training has been seen as mainly a supplemental tool for improving neurological factors to increase force production at higher velocities but used in isolation considered as providing too small of a stimulus to maintain or increase muscle size and maximal strength (Cormie et al., 2011a; Slimani et al., 2016; Suchomel et al., 2018).

A recent review from 2021 by Grgic et al, challenges this perception by looking at studies comparing heavy load resistance training vs. plyometric training in the same cohort, rather than assessing the effects from individual studies(Grgic et al., 2021). They found similar effects on whole muscle hypertrophy on the lower extremities, although in mostly untrained participants. The magnitude of each adaption can depend on the exercise modality and different regional adaptions in hypertrophy have also been reported (EARP et al., 2015; Franchi et al., 2018; Haun et al., 2019). In a study by Earp et al. (2015) heavy squat vs. low-load squat jump resulted in similar increases of overall CSA of the quadricep femoris, but inhomogeneous adaptions at the proximal, middle and distal sites (EARP et al., 2015). This is thought to be a consequence of region specific muscular demands between higher load and low velocity vs. lower load and high velocity movements resulting in regional muscle size adaptions, as well as specific architectural adaptions of pennation angle, fascicle length and fibre type (Blazevich et al., 2003, 2006; EARP et al., 2015; Grgic et al., 2021).

Overall, this raises the question of whether power and plyometric training have a greater muscle architectural effect than previously though stimulating both neural and structural adaptions more specific to high movement velocities. Power and plyometric training may therefore be considered an effective in-season training program in isolation for team-sport athletes needing to produce high force at high velocities (Chelly et al., 2010; Cormier et al., 2021; Grgic et al., 2021; Sammoud et al., 2022; Sánchez et al., 2020; Slimani et al., 2016). However, many team-sports already involve a large number of explosive actions, and these athletes might not respond to any additional power/plyometric training (Cormier et al., 2021; Suchomel et al., 2018). It could also compromise their ability to produce force maximally which has shown benefits across the force-velocity spectrum (Cormie et al., 2011a; Suchomel et al., 2016, 2018; Taber et al., 2016). These athletes may need a high load stimulus to further develop their force production, but this type of training typically demands more recovery time and could challenge their capacity to perform optimally in handball related activities in-season (Cormier et al., 2021).

There is a lack of direct comparisons between these training modalities in isolation, especially in female team sport athletes, suggesting an area in need of further investigation. The purpose of this article will therefore be to investigate the effects of in-season heavy resistance training vs. power and plyometric training on muscle strength, -size and -architecture on female handball players.

1.1 Outcomes and hypothesis

Outcome variables will be bodyweight, fat-free mass, cross-sectional area, muscle thickness, pennation angle, fascicle length, 1RM bench, 1 RM squat, Keiser (absolute, relative) and MVC. The hypothesis is that heavy load resistance training and power/plyometric training will have similar effects on FFM, but different regional adaptions on cross-sectional area and muscle thickness of the m. vastus lateralis and m. rectus femoris, specifically a larger increase in distal regions from power/plyometric training compared to a larger increase in the middle and proximal regions from heavy load resistance training. Pennation angle is also hypothesized to increase in both groups, but to a larger degree in the heavy load resistance group. Fascicle length is hypothesized to increase in a larger degree in the power/plyometric group. Strength parameters is hypothesized to increase in the HRG and decrease in the PPG.

2 Theoretical framework

2.1 Physical demands and performance determining factors of handball performance

Team sport performance is a complex and involves various physical, technical, and tactical abilities specific to each sport (Hermassi et al., 2015; Karcher & Buchheit, 2014; Michalsik & Aagaard, 2014; Stolen et al., 2005). In order to excel at the highest level, athletes must possess a certain level of physiological abilities to meet the demands encountered during training and match scenarios (Manchado et al., 2013; Stolen et al., 2005). Athletes need a minimum level of maximal oxygen consumption as well as the ability to perform repeated bouts of various high-intensity actions (Falch et al., 2021; García-Sánchez et al., 2023; Manchado et al., 2013). While both aerobic and anaerobic capacities contribute to overall performance, anaerobic abilities, such as sprinting and jumping, are often considered the most crucial factors often preceding match deciding events (Falch et al., 2021; Faude et al., 2012; Karcher & Buchheit, 2014; Slimani et al., 2016; Stolen et al., 2005).

Handball is a rigorous contact sport involving a multitude of fast, intense and dynamic actions such as jumping, sprinting, throwing and duels (Chelly et al., 2010; Hermassi et al., 2015; Manchado et al., 2013; Michalsik & Aagaard, 2014; Póvoas et al., 2012). While activities such as walking and standing still makes up ~70 % of playing time, the repeated exposure to high intensity events, especially body contacts, requires high levels of force production at various velocities to withstand the neuromuscular load experienced during games and outperform your competitors (Karcher & Buchheit, 2014; Manchado et al., 2013). Given the physical demands of handball, athletes at the elite level demonstrate significantly higher levels of force producing ability compared to their amateur counterparts (Manchado et al., 2013; Suchomel et al., 2016; Wagner et al., 2017).

2.2 The importance of muscular strength in handball performance

In handball force may have to be exerted against gravity, an opponent's body mass or a projectile. A limiting factor in these actions is the athlete’s maximal and explosive muscular strength (Blazevich et al., 2006; Suchomel et al., 2016). Maximal muscular strength refers to the capacity of generating high levels of force at low velocities and plays a vital role in actions that require generating high levels of force against heavy loads or resistance, such as overcoming opponents in duels and establishing advantageous positions (Karcher & Buchheit, 2014; Póvoas et al., 2012; Suchomel et al., 2016). On the other hand, explosive muscular strength is defined as the ability to rapidly produce force or generate high levels of force in a short amount of time, often termed as rate of force development (RFD) and enables athletes to perform explosive jumps, sprints, and throws (Karcher & Buchheit, 2014; Póvoas et al., 2012; Suchomel et al., 2016). Consequently, explosive strength is viewed as a vital component of performance due to the fact of encountering limited time to produce force in many team-sports.

A force-velocity relationship exist, described as the inverse relationship between force production and movement velocity during muscular contractions (Cormie et al., 2011a). Higher loads can be moved by producing more force, but at a lower velocity, whereas lighter loads can be moved at higher velocities with a lower production of force. Force and velocity therefore exists on a spectrum with maximal force and maximum velocity at each end (Taber et al., 2016). Several studies have indicated a relationship between maximal strength and explosive strength, with some indications estimating maximal muscular strength may account for up to 80% of the variance in voluntary RFD (150–250 ms) (Andersen & Aagaard, 2006;

Suchomel et al., 2016). Developing both forms of muscular strength is therefore crucial for handball players to excel in different aspects of the game.

2.3 Factors determining muscular strength

Muscular strength is determined by a complex interplay of neurological and morphological factors, which involve the intricate connection between the nervous system and the musculoskeletal system, with ability to express maximal- and explosive strength being influenced by specific morphological- and neural factors (Cormie et al., 2011a; Suchomel et al., 2018).

2.3.1 Muscle morphological factors

Muscle morphology refers to the structural characteristics and arrangement of muscle fibers, fascicles, and other components within a muscle (Blazevich et al., 2006; Cormie et al., 2011a; Lee et al., 2021; Methenitis et al., 2016). It includes various factors such as muscle size, fiber type distribution and muscle architecture.

2.3.1.1 Muscle size

Muscle size, specifically indicated by measures such as muscle thickness or cross-sectional area (CSA), has a significant impact on muscular strength, especially maximal strength (Blazevich et al., 2006; Cormie et al., 2011a; Lee et al., 2021). The maximal force generated by individual muscle fibers shows a direct proportional relationship with its CSA irrespective of fibre type (Cormie et al., 2011a). This increased cross-sectional area allows for a greater number of muscle fibers to be activated simultaneously during contraction, resulting in a higher force output (Blazevich et al., 2006). Therefore, handball players with larger muscle size have an advantage in generating force supported by studies comparing handball players at different levels of competition where elite handball players consistently exhibit greater muscle CSA and overall muscle size compared to non-athletes or amateur players (Manchado et al., 2013; Wagner et al., 2017).

Increases in muscle fiber size, referred to a muscle hypertrophy, is an adaptive response to a combination of factors including induced muscle disruption, metabolic stress, and mechanical tension, with the latter being viewed as the primary driver (Travis et al., 2020). While hypertrophy can occur in response to a wide range of training methods, using different loads and velocity, methods that elicit sufficient mechanical tension and metabolic stress is viewed as the most effective (Arntz et al., 2022; Grgic et al., 2021; Schoenfeld, 2010; Schoenfeld et al., 2017; Suchomel et al., 2018).

2.3.1.2 Regional distribution of muscle mass

Increases in muscle size is not always uniform and muscle mass distribution, both between muscle groups and within individual muscles, show region specific differences among athletes from different sports and competition level (Handsfield et al., 2017; Haun et al., 2019; Miller et al., 2021; Travis et al., 2020). While muscle size can be similar, when comparing strength between different athletes from different sports, their expression of force and velocity can differ (Travis et al., 2020). These variations in muscle mass distribution are believed to enable different regions of the muscle to fulfill distinct functional roles (EARP et al., 2015). It is hypothesized that certain regions of the muscle may be particularly well-suited for high-force production, while other regions may be more adept at facilitating high velocity movements. This can be seen when investigating muscle group specific distribution in sprinters which suggest that, particularly large hip and knee flexors and extensors, can be advantageous for fast sprinting (Handsfield et al., 2017; Miller et al., 2021). Regional distribution along the length of a muscle can also impact performance, with muscle mass closer to the joint's axis of rotation, reducing the moment of inertia, seen as beneficial for high velocity movements, but not that important during high load low velocity movements where forces can be developed over a longer period of time (Abe et al., 2000; EARP et al., 2015; Myers & Steudel, 1985). This is supported by selective muscle recruitment during movements with varying levels of force and velocity, as well as non-uniform regional hypertrophy adaptions (EARP et al., 2015; Haun et al., 2019; Travis et al., 2020).

2.3.1.3 Muscle fibre type

Composition of muscle fibre type will also influence the expression of force at different velocities (Cormie et al., 2011a; Plotkin et al., 2021). Skeletal muscle consists of several muscle fiber types, which range along a spectrum from slow to fast (Plotkin et al., 2021). Type I fibers, also known as slow-twitch fibers, exhibit slower twitch speeds and demonstrate a greater resistance to fatigue. On the other hand, Type IIa fibers, referred to as fast oxidative glycolytic (FOG) fibers, display higher twitch speeds compared to Type I fibers but have a lower resistance to fatigue. Lastly, Type IIx fibers, known as fast glycolytic fibers, have the fastest twitch speeds but are highly susceptible to fatigue. In addition to the more pure fibre types described above , muscle fibers can also display hybrid characteristics with the existence of I/IIa fibers, IIa/IIx fibers, and I/IIa/IIx fibers (Medler, 2019). These unique characteristics differentiate the functional utility of each fiber type in various sport related activities. Athletes with a higher proportion of type I fibers have shown greater success in endurance-based events characterized by slower and longer distances while individuals with a higher proportion of type II fibers have been associated with better performance in high-velocity, shorter-duration events (Cormie et al., 2011a; Plotkin et al., 2021). Muscle fiber type composition therefore has significant role in predicting sports performance (Cormie et al., 2011a; Lee et al., 2021; Plotkin et al., 2021).

Since fast-twitch type II fibers have a higher force-generating capacity at high velocities compared to slow-twitch fibers, they are particularly important for explosive movements in handball such as jumping, sprinting, and throwing. The proportion of fast-twitch and slow-twitch fibers in a muscle varies among individuals and it is estimated that approximately 45% of the variation in muscle fiber type is influenced by genetic factors while studies have also shown that fiber type transformations can occur as a result of intense training or detraining, leading to changes from type I to type II fibers and vice versa (Andersen et al., 2005; Cormie et al., 2011a; Larsson & Ansved, 1985; Simoneau & Bouchard, 1995). Resistance training has induced changes within type I and II fibres, and reductions in type IIx isoforms at the expense of type IIa isoforms have been observed (Cormie et al., 2011a). Under chronically high load environments, it is believed that a shift towards a predominantly IIa fiber type occurs, as it offers more economical characteristics. Additionally, periods of detraining have shown a conversion back to a type IIx fiber composition, with levels surpassing those observed prior to strength training (Cormie et al., 2011a). Both fast- and slow twitch muscle fibers is capable of hypertrophic changes, but fast twitch fibers may increase to a greater extent due to its physiological characteristics and the athletes and training stimuli associated with it (Cormie et al., 2011a; Travis et al., 2020). Resistance training performed at slower speeds and with relatively high loads (>70% of one-repetition maximum) leads to a transition from IIx and IIx/IIa hybrid fibers to a predominantly IIa fiber phenotype, with minimal changes observed in pure type I fibers, while training at higher speeds typically results in a smaller reduction in IIx and IIx/IIa fibers with combined with a decrease or transition of type I fibers towards a faster phenotype (Plotkin et al., 2021).

2.3.1.4 Muscle architecture

Muscle architecture refers to the structural characteristics of muscles, including factors such as the pennation angle and fiber length, which significantly influence muscular strength and force production potential (Blazevich et al., 2006; Cormie et al., 2011a; Lee et al., 2021). Muscles with a large pennation angle, defined as the angle between the muscle’s fascicles and the line of action, have a relatively higher physiological cross-sectional area, leading to increased force-production potential (Blazevich et al., 2006; Cormie et al., 2011a; Kruse et al., 2021). The higher pennate angle allows for more muscle fibers to be arranged in parallel, contributing to greater force generation. However, due to their shorter length, muscles with a large pennation angle have fewer sarcomeres arranged in series. As a result, they exhibit high force production potential but at lower velocities (Blazevich et al., 2006; Cormie et al., 2011a). Increases in pennation angle is often seen together with increases in muscle size, and is by some viewed as a by-product of hypertrophy functioning as an efficient muscle packing strategy whereby short fibers can be packed into a limited volume, as opposed to a specific architectural adaption to increase maximal force production at low velocities (Lieber, 2022).

In contrast, longer muscle fibers are more effective at producing force at higher shortening velocities and length ranges due to an increased number of serially arranged sarcomeres (Blazevich et al., 2006). The maximum shortening velocity of a muscle fibre is proportional to its length when assuming a constant level of activation since a greater number of sarcomeres in series require less shortening at a given maximal contraction, resulting in reduced shortening duration (Blazevich et al., 2006; Cormie et al., 2011a). This characteristic allows for the generation of high force at high velocities and correlations have been found between the length of fascicles in the vastus lateralis and gastrocnemius lateralis muscles and performance in 100-meter sprints, both in men and women (Abe et al., 2001; Kumagai et al., 2000). Sprinters also exhibit significantly longer fascicle lengths in the vastus lateralis, gastrocnemius medialis, and gastrocnemius lateralis muscles compared to long-distance runners and untrained individuals (Abe et al., 2000). The exact cause of these observations remains uncertain, as it is unclear whether the observed differences in fascicle length are a result of genetic predisposition or an adaptation to the specific training methods commonly used by sprinters, such as high-intensity sprint training and high-intensity strength/power training (Cormie et al., 2011a). Nevertheless, increases in fascicle length has been seen in response to eccentric training with possible additional effect of high velocity, as well as long ranges of motion (Timmins et al., 2016). As fascicle length is influenced by pennation angle, changes can also occur due to alterations in muscle size (Lieber, 2022; Travis et al., 2020).

2.3.2 Neurological factors

Neurological factors play a critical role in determining muscular strength through the precise and coordinated activation of muscles by the nervous system (Cormie et al., 2011a; Gabriel et al., 2006). This include mechanisms such as motor unit recruitment, firing frequency, synchronization, and inter-muscular coordination (Cormie et al., 2011a).

2.3.2.1 Motor unit recruitment and synchronization

Motor unit recruitment and synchronization are key neurological mechanisms that can influence muscular strength and force production (Cormie et al., 2011a; Folland & Williams, 2007; Suchomel et al., 2016). The number and type of motor units recruited play a crucial role in determining the amount of force a muscle can generate, following Henneman's size principle (Cormie et al., 2011b; Henneman et al., 1965, 1974). During voluntary contractions with increasing force, smaller motor units that include slow-twitch type I fibers are recruited before larger that include fast-twitch type IIa/IIx fibers (Suchomel et al., 2018). Motor unit recruitment involves activating a greater number of motor units, particularly high-threshold motor units known for their higher force-generating capacity and is increased by performing movements that require high force output or RFD (Cormie et al., 2011a; Gabriel et al., 2006; Suchomel et al., 2018). Furthermore, the ability to activate and synchronize motor units more effectively can also lead to enhanced maximal force production and rate of force development and can be enhanced by training methods requiring high levels of force or velocity (Cormie et al., 2011a; Folland & Williams, 2007; Komi, 1986; Semmler & Enoka, 2000; Suchomel et al., 2018).

2.3.2.2 Firing frequency

The firing frequency of motor units, defined as the rate of neural impulses transmitted from the a-motoneuron to the muscle fibers, plays a crucial role in muscle force generation (Cormie et al., 2011a; Suchomel et al., 2018). Increasing the firing frequency therefore increases the generation of force produced during muscle contractions. It can as well affect the rate of force development (RFD) of muscle contractions by initially firing at higher frequencies, followed by a rapid decline. This high initial firing frequency, associated with an increase in the number of doublet discharges, contributes to an elevated RFD, even if maintained for a short period of time (Van Cutsem et al., 1998). Firing frequency may be enhanced by performing movements requiring high RFD (Van Cutsem et al., 1998).

2.3.2.3 Inter-muscular coordination

Inter-muscular coordination refers to the precise activation, both in terms of magnitude and timing, of the agonist, synergist, and antagonist muscles during movement (Cormie et al., 2011a). For optimal force generation in the intended direction of movement, it is essential to supplement agonist activation with increased synergist activity and reduced co-contraction of the antagonists (Cormie et al., 2011b; Gabriel et al., 2006). This coordinated activation of muscles is necessary to generate the maximum possible force during movements. The "triple extension" action, involving extension of the hips, knees, and plantarflexion of the ankles, commonly observed in jumping and sprinting, relies on the intricate interaction of uni- and multi-articulate musculo-tendinous units performing various actions (Cormie et al., 2011a).

2.4 Strength training for muscular strength

Strength training involves a wide range of exercises and methodologies designed to improve muscular strength, including heavy load resistance training, optimum power load training, weightlifting, plyometrics, eccentric training, and combinations of these methods (Cormie et al., 2011b; Cormier et al., 2021). These different types of strength training have been shown to elicit positive adaptations in various neural and morphological factors, such as muscle cross-sectional area, architecture, motor unit recruitment, firing frequency, and motor unit synchronization (Suchomel et al., 2018). To optimize athletic performance, it is crucial to implement strength training programs that promote favourable muscle morphological and neuromuscular adaptations specific to the demands of the sport (Cormier et al., 2021).

2.4.1 Strength training in team sport and handball

Team-sport athletes use various training programs that target specific force and velocity qualities of muscular strength (Cormier et al., 2021; Suchomel et al., 2016). Heavy load resistance training have traditionally been extensively used in team sport athletes due to its ability in improving force production, but several methods have become popular during the last decades (Arntz et al., 2022; Cormie et al., 2011a; Cormier et al., 2021; Grgic et al., 2021; Ramirez-Campillo et al., 2022). Methods such as weightlifting, ballistic training and plyometric training have increased in popularity due to the similarity in achieved force and velocity compared to many high intensity actions encountered in team sport (Cormier et al., 2021). Combining heavy load resistance training with lighter load variations have been recently been hypothesized to maybe achieve greater improvements in muscle strength over heavy load resistance alone, by maximizing a range of force and velocity specific morphological and neural adaptions (Cormier et al., 2021). While many methods has shown benefits in improving force production, implementing them in a team sport setting is challenging and knowledge regarding implementation in-season is vital (Cormier et al., 2021)

2.4.2 Heavy load resistance training

Heavy load resistance training is a commonly used and extensively researched training method (Cormier et al., 2021). This method typically involves lifting weights or using resistance machines with a focus on challenging the muscles to overcome significant resistance. It focuses on high force output and consequently is performed at low velocity due to the force-velocity relationship (Cormie et al., 2011a; Suchomel et al., 2018). It has been shown effective at improving muscular strength, both maximal and explosive, and increased maximal dynamic strength has been associated with sprint performance and reductions in injury risk (Cormier et al., 2021; Taber et al., 2016; Wisløff et al., 2004). Increasing the ability to produce absolute maximal force can lay a foundation for generating force across a wide range of velocities (Taber et al., 2016). Muscular strength development from heavy load resistance training stems mainly from its significant effect on muscle CSA as well as factors such as muscle fibre type, pennation angle and neural adaptions (Cormie et al., 2011a, 2011b; Suchomel et al., 2018). Training status needs to be taken into account when implementing heavy load resistance training, and its effect on force production is generally bigger on weaker athletes while stronger athletes may respond better to more advanced (combined training) or velocity specific training methods (Cormier et al., 2021). While it is a proven method for improving muscular strength it may lead to excessive muscle damage compromising recovery during the competitive season (Cormier et al., 2021).

2.4.3 Power training

Power training involves training that emphasizes ability to overcome resistance in the shortest possible time (Taber et al., 2016). Power is a work rate term, represented by the equation Power = Force x Velocity, which highlights that power output can be enhanced by increasing either force or velocity, or both (Taber et al., 2016). This can be achieved through various training methods, including heavy resistance exercises to enhance force production, as well as explosive exercises to enhance velocity. While maximum force and maximum velocity is produced at polar ends of the force-velocity continuum, maximum power ouput being the result of both exist in the middle (Taber et al., 2016). Training at the load which elicits the greatest power output is referred to as “Optimal power load” training, and is often used in team sports settings due to its practicality and ability to enhance power across the force-velocity continuum (Cormie et al., 2011b; Cormier et al., 2021; Freitas et al., 2018). It enhances power development in athletes via achieving high force and velocity, without using heavy loads that may reduce muscle damage and recovery demands during the season (Cormier et al., 2021). Nevertheless, it is seen as inducing to little mechanical tension to elicit a hypertrophic responses similar to heavy load resistance training, which may compromise optimal force development (Cormie et al., 2011a).

2.4.4 Plyometric training

Plyometric training involves explosive movements utilizing the stretch-shortening cycle, which is characterized by combining an eccentric muscle action with a subsequent powerful concentric muscle action (Cormier et al., 2021). The stretch-shortening cycle during plyometric exercises allows for energy conservation and generates increased propulsive forces during the concentric phase of the movement (Turner & Jeffreys, 2010). It has shown to be effective for muscle strength, sprinting, jumping and change of direction (Arntz et al., 2022). This is attributed to enhanced neuromuscular adaptions such as increased motor unit recruitment, firing frequency, synchronization and better inter-muscular coordination as opposed to morphological factors (Arntz et al., 2022). Plyometric training has been seen as providing to little mechanical tension to elicit substantial increases in muscle size compared to heavy load resistance training, but a recent review conducted by Grgic et al. (2021), challenged this by comparing the effects of these training modalities on the same cohort (Grgic et al., 2021). The findings revealed similar effects on whole muscle hypertrophy in the lower extremities, albeit primarily in untrained participants. A following systematic review by Arntz et al (2022) revealed small to moderate effects across different ages, sexes, and training experiences, with a relatively bigger effect in non-athletes compared to athletes (Arntz et al., 2022).

2.5 Summary

This theoretical framework shows the importance of physical abilities, such as sprinting, jumping, throwing and duelling handball performance (Falch et al., 2021; Faude et al., 2012; Karcher & Buchheit, 2014; Slimani et al., 2016; Stolen et al., 2005). The limiting factor for performing these actions is muscular strength laying the foundation for producing force across a wide range of velocities (Blazevich et al., 2006; Suchomel et al., 2016). Muscular strength is influenced by a complex interplay of neurological and morphological factors (Cormie et al., 2011a; Suchomel et al., 2018). Morphological factors such as muscle size, fiber type, muscle mass regional distribution and muscle architecture, as well as neural factors such as motor unit recruitment and synchronization and firing frequency will determine the expression of force during various velocities (Cormie et al., 2011a; Cormier et al., 2021; EARP et al., 2015). Especially muscle size is a major determining factor for force production and most team sport athletes utilizes training methods aiming for inducing hypertrophy (Cormie et al., 2011a; Cormier et al., 2021). Traditionally heavy load resistance training has been extensively used due to its effect on force production via increased muscle size, but it can be challenging to implement during in-season due to recovery needs (Cormier et al., 2021). High-force, high-velocity training methods have gained popularity, but their effectiveness in inducing hypertrophy requires further research.

3 Method

3.1 Study design

The aim of this study is exploring the effects of in-season heavy load resistance training versus power and plyometric training on body composition, muscle strength, size, and -architecture. A non-blinded randomized controlled trial (RCT) design was employed, in which female handball players from two teams were randomly assigned to either a heavy load resistance training group (HRG) or a power and plyometric training group (PPG). Randomization into two groups was done in both teams by pair matching based on playing position to reduce selection bias, ensure comparable baseline characteristics and exposure to similar physical demands during the season. Blinding was not possible due to the nature of the intervention. Prior to baseline testing, each group underwent a familiarization period for testing procedures to minimize task learning effects on changes between pre- and post-tests. The training intervention lasted for a period of 12 weeks, after which a post-test was conducted.

3.2 Participants

Female handball players were recruited from two local senior teams (n=34) during the spring of 2022. Subjects at sub-elite level from the age of 16-35 years with prior strength training experience were included. Players with current injuries that would limit their performance during the training intervention and testing, or those who were pregnant, were excluded from the study. One player dropped out pre-intervention after being randomized into PPG. Two players dropped out during the training intervention due to injury and motivation respectively, resulting in a total of 31 participants which completed the study. A total of 31 female sub-elite handball players (age 20±2.78 years, height 170±5.95 cm, weight 68±11.1 kg) were randomized into a heavy load resistance group (heavy-load; n=16) and power and plyometric group (power-plyo; n=15). Baseline characteristics are presented in the following table (Table 1).

Table 1: Baseline characteristics

Group	Heavy-load	Power-Plyo
Sample size (n)	16	15
Age	19.5±2.8	20.4±2.8
Weight	70.2±13.9	65.6±6.8
Height	169.9±6.2	170.4±5.9

Note: Values are presented as mean ± SD. Cm, centimeter; Kg, kilograms; SD, standard deviation.

Subjects received information about the study both in written and oral form (appendix X). Participation was voluntary and subjects could withdraw at any point. Written consent was obtained prior to testing. The study was approved by the ethical board of the faculty of sports science and physical education at the University of Agder (appendix Y), and the Norwegian Centre for Research Data (appendix XY) and was conducted in agreement with the Declaration of Helsinki.

3.3 Training intervention

The 12-week training intervention consisted of two weekly sessions (A and B) for both groups. Sessions A (high volume) and B (low volume) differed in their total volume, with the goal of facilitating easier implementation and timing of the training sessions to align with match days during the season. One session per week, usually session A, was supervised by project members to ensure that proper form, technique and progression were maintained during the training. Lifting velocity was tracked using VmaxPro® (Blaumann & Meyer, Sports Technology UG, Magdeburg, Germany; VMP) sensors to measure and ensure correct load and effort. Since the players were not familiar with using RIR, we measured velocity loss during squats in the HRG during the initial weeks to ensure the players were close to failure (velocity of <0.4 m/s at ~1RIR.(Izquierdo et al., 2006) Participants in PPG were instructed to give maximal effort and minimize loss of velocity with visual and verbal feedback. For the push jerk exercise, the initial weeks were used to find a load that ensured a minimum of 1 m/s, this load was then maintained throughout the intervention. The heavy load resistance program involved performing 2-6 sets of exercises at intensities of approximately 80-85% of 1RM, while the power and plyometric groups performed 2-4 sets of power exercises at lower intensities of ≤50% 1RM, in combination with 75-90 plyometric bodyweight jumps. HRG and PPG training programs differ in total repetitions due to the different characteristics of each training modality. There is no consensus on how to match programs in terms of stimuli and overall workload so each program is based on current best knowledge on what has shown training adaptions in previous studies aiming for an optimal stimulus in both groups. XPS Network (Sideline Sports US LLC, Reykjavik, Iceland) was used for monitoring the participants during the intervention with players reporting sessions completed. Week 1 was performed as a familiarization period with reduced intensity (2-3RIR), effort (80-90% effort) and volume (2 sets), before performing the full training program from week 2.

Table 3: Training group modality

Heavy-load group	Power-Plyo group
Group training only with heavy loads at intensities of 80-85% of 1RM	Group training only power at intensities of ≤50% 1RM combined with bodyweight plyometric jumps

Table 4: Heavy load training program

Session A				
Exercises	**Sets**	**Reps**	**Rest**	**RIR/intensity**
Parallel squat	3	5	3 min	1RIR
Split squat	3	5	3 min	1 RIR
Superset: hip thrust	3	5	3 min	1 RIR
Superset: one leg calf rise	3	10	2 min	High
Romanian deadlift	2	5	3 min	1 RIR
Superset: bench press	3	5	3 min	1 RIR
Superset: pullups/pulldowns	3	5	2 min	1 RIR
Shoulder press bar or dumbbells	2	5	2 min	1 RIR
Weighted sit-ups	2	10	2 min	High
Session B				
Parallel squat	2	5	3 min	1 RIR
Superset: nordic hamstring curl	2	5	3 min	High
Superset: superman/rollouts	2	10	2 min	High
Bulgarian lunges	2	5	3 min	1 RIR
Bench press with dumbbells	2	5	3 min	1 RIR
Superset: cable row or 1 – arm dumbbell rows	2	5	2 min	1 RIR
Superset: Triceps dumbbell press	2	5	2 min	1 RIR

Table 5: Power-plyo training program

Session A

Exercises	Sets	Reps	Rest	RIR/intensity
Squat jump	4	5	3 min	50% 1RM
Push jerk	3	5	2 min	Velocity
Superset: Explosive bench press with elastic bands	3	5	2 min	50% 1RM
Superset: Single leg hip thrust jump	3	5	3 min	BW/max
Drop jump	3	10	2 min	BW/max
Superset: Kettlebell swing	3	8		12 kg +
Superset: Medicine ball chest throw	3	5	2 min	2-4 kg
Superset: Bulgarian jumps	3	5	3 min	BW/max
Superset: Box jumps	3	10	2 min	BW/max
Reverse rowing/med-ball slam	3	5	2 min	BW/max
Session B				
Squat jump	3	5	3 min	50% 1RM
Superset: Single leg hip thrust jump	2	5	2 min	BW/max
Superset: Medicine ball chest throw	2	5	2 min	2-4 kg
Hurdle jumps	2	10	2 min	BW/max
Split squat jumps	3	5	3 min	BW/max
Horizontal jumps	2	5	2 min	BW/max
Superset: Box jumps	2	10	2 min	BW/max
Superset: Reverse rowing	2	5	2 min	BW/max

Note: new exercises included in weeks 6-12

3.4 Testing procedures

Players performed several tests indoors in a lab setting at two occasions. First initial familiarization testing and second subsequent baseline testing. Test protocols were standardized regarding testing order, warm-up, rest and food and water intake. Measurements were obtained from ultrasonography (Telemed ArtUS EXT-1H, IT, 70 Hz, Vilnius, Lithuania: probe LV8-5N60-A2, 60mm), Dual-Energy X-ray absorptiometry (DXA) (GELunar Prodigy, General Electric Company, Madison, Wisconsin, USA), 1-repetition maximum Parallel Squat, 1-repetition maximum Benchpress, Keiser Leg Press (A300, Keiser Corporation, Fresno CA, USA) and isometric maximum voluntary contraction (MVC) in 90 degrees knee extension.

3.4.1 DXA

Dual-Energy X-ray absorptiometry (DXA) (GELunar Prodigy, General Electric Company, Madison, Wisconsin, USA) was used to assess total body and leg fat-free mass. Testing was performed by trained members of the research project. Height and weight were measured before the DXA scan using a mobile floor weight (Seca 877) and an altimeter (Seca 216), respectively. Subjects were instructed to fast at least 2 hours prior to the scan. Calibration was performed ahead of each day of testing according to the manufacturer's guidelines. Images were analysed using encore software (version 14.10.022; GE-Healthcare).

3.4.2 Ultrasound

Muscle thickness, pennation angle and fascicle length of m. vastus lateralis and muscle thickness and cross-sectional area of m. rectus femoris was assessed by ultrasonography (Telemed ArtUS EXT-1H, IT, 70 Hz, Vilnius, Lithuania: probe LV8-5N60-A2, 60mm). Subjects were instructed to lay relaxed on the massage table with their knee extended 180 degrees. The muscle thickness and cross-sectional area (CSA) measurements were taken directly between the hip and knee joint at the 33%, 50% and 67% at the femur length between the greater trochanter and lateral epicondyle of the femur, similar to Earp et al, 2015.(EARP et al., 2015), while muscle architecture was assessed approximately at the 50% position. Measuring sites were located by palpating and measuring tape, and all measurements were performed on the preferred jump leg. To ensure consistent measurement location, probe measurement positions were marked with a waterproof pen during the familiarization session and subsequently transferred onto a transparent sheet using moles, birthmarks, and scars as reference points. Measurement positions were then located during the pre-and post-tests by referencing the markings on the thigh from the transparent sheet and comparing them with previous images taken at the same location. After covering the probe with water-soluble transmission gel (Aquasonic 100 ultrasound transmission gel; Parker laboratories inc., Fairfield, NJ, USA), it was gently placed against the skin to not cause errors in measurements by excessive pressure (Lixandrão et al., 2014; Sarto et al., 2021). Two trained test leaders performed the ultrasound measurements. The probe was held across the direction of the respective muscle fibers to capture images of muscle thickness and CSA, while it was held parallel with the fibers of m. vastus lateralis to assess muscle architecture. Images were saved and then later analysed manually using ImageJ (Wayne Rasband, National Institutes of Health, Bethesda/MD, USA). Muscle thickness was measured by drawing a vertical line between at the upper and deeper *aponeurosis* at positions determined by recognizable reference points (such as connective tissue and the femur bone) to ensure measurements were taken at the same place pre- and post-intervention. CSA was measured by using the freehand function to draw lines around the inside of the *aponeurosis.* Due to the size of the m. rectus femoris of a lot of the subjects, several pictures taken at the 50% and 67% sites could not fit entirely within the view of the probe. Therefore, reference points or a given distance from where the muscle thickness was measured were used to extrapolate or cut the images at the sides. To determine the pennation angle, a manual angle function was used to measure the angle of visible muscle fibers relative to the average direction of the deeper aponeurosis. Fascicle lengths were then estimated using average pennation angle (2-3) and average muscle thickness (measured at three points) put into the formula muscle thickness/(sinus(pennation angle* π)/180))

3.4.3 Squat 1RM

An estimation of 1 repetition maximum parallel squat was used to assess lower body maximal strength. Subjects were instructed to achieve a squat depth where the upper thighs were parallel to the ground, visually monitored by the research team. During the familiarization phase, participants estimated their one-repetition maximum (1RM), which they subsequently attempted to surpass during baseline testing. The testing protocol started with five repetitions at 50% of the estimated 1RM, followed by 2-3 repetitions at 70% 1RM, and 1-2 repetitions at 90% 1RM. Subsequently, participants performed 2-3 attempts at a designated 1RM load. If a 1RM attempt was successful, the load was incrementally increased until the participant could no longer lift the weight, or the successful attempt was close to failure. Rest periods varied between 1-3 minutes, increasing in duration as the loads increased.

3.4.4 Benchpress 1RM

One-repetition maximum (1RM) estimation of the bench press was used to evaluate upper body maximal strength. Although the testing was part of a bench press power profile, only the estimated 1RM data were utilized in this study. Participants were instructed to adopt a conventional grip width, with their hands positioned slightly wider than shoulder-width apart. The barbell was required to make contact with the chest during each repetition. The warm-up started with 1-5 repetitions using only the barbell, gradually increasing in velocity. Participants incrementally increased the load towards 90% of their 1RM, with measurements recorded at a minimum of five distinct loads prior to 1RM testing. Rest periods, ranging from 1-3 minutes, were incrementally increased with the increasing load.

3.4.5 Keiser Leg press

A Keiser A300 seated pneumatic leg press machine was used to assess maximal strength in the lower limbs as absolute force (newton), estimated from a 10-repetition FV test pre-programmed in the Keiser software. The test starts at approximately 15% 1RM followed by incremental increase loads based on a 1 RM estimate obtained at familiarization. The seating position was set at ~90˚ knee angle aiming for a vertical femur with adjusted seating settings noted and used at pre- and post-test. Subjects were instructed to push with maximal effort and intent during the initial concentric push while not resisting during the eccentric part of the movement. The test was performed until muscular failure and 1RM was obtained. Rest periods (10-60 seconds) increased as the loads increased. The FV test used measures several aspects of force and velocity, such as peak force, velocity and power, but this present study will only use the 1RM measure for further analysis (Redden et al., 2018).

3.4.6 MVC

An isometric maximum voluntary contraction of knee extensors was performed to assess maximal strength of the dominant jump leg. The test was performed at 90˚ knee angle sitting at bench platform with handles at each side with the back of the knee touching the edge of the bench. A force cell was attached to the ankle and attachments positions were noted for use at pre- and post-test. Warmup consisted of subjects pushing at 50-, 70- and 90% maximum force for 2-3 seconds with a 30 second rest period. Following a 1 min break, subjects were told to push as hard as they could for a period of 3-5 seconds. Each subject got 3 attempts with >30 second rest period. If recording the best attempt at the last rep, one more attempt was given. MVC was measured using a force cell (1000hz) from Musclelab (version 10.5.69.4815, Ergotest Innovation, Stathelle, Norway).

3.5 Statistical analysis

To assess whether the data were normally distributed, a Shapiro-Wilk test was conducted as well as an examination of the mean, median, skewness, kurtosis, and Q-Q. All data, except for PPG changes in body weight, squat, and MVC, were determined to be normally distributed. An independent samples t-test was used to evaluate between-group differences in percentage change from baseline, in addition to a Mann-Whitney U test for non-normally distributed data. To assess within-group changes from pre- to post-test, a paired samples t-test and Wilcoxon signed-rank test were performed. A significance level was established at $p < 0.05$, and confidence limits were set at 95%. Statistical analyses were conducted using Jamovi (2022, Version 2.3, the Jamovi project, Sydney, Australia). Descriptive baseline characteristics are presented as mean values and standard deviations (SD). Muscle size and strength results are reported as mean, percentage change, effect sizes (ES), SDs, confidence intervals, coefficients of variation (CV), and p-values. The effect size (ES) was calculated using Cohen's d.

4 Method discussion

4.1 Study design

The present study employed a randomized controlled trial (RCT) design, which is a common approach when assessing the efficacy of strength training interventions. RCTs have several benefits, including reducing the potential for bias and confounding factors and the ability to assess cause-effect relationships (Beato, 2022; Hariton & Locascio, 2018; Moher et al., 2001). This study design involved randomly assigning participants to different intervention groups, acting as active control groups, allowing for a comparison between the training interventions. A limitation in the present study is the lack of an additional non-strength training control group which would have allowed for the assessment of what adaptions were caused by the interventions per se. This usually requires a larger sample size to ensure sufficient statistical power while also potentially being unethical on the basis of one group negating the benefits of in season strength- and power-training commonly used in team sports (Beato, 2022). Randomization helps to establish an even distribution of potential bias and confounding factors, such as age, training load and baseline fitness levels, which can affect the outcomes of the intervention (Beato, 2022; Hariton & Locascio, 2018; Moher et al., 2001). Random assignment into either a PPG or HRG was performed in both teams, minimizing the potential influence of varying training loads between the teams, as opposed to dividing the entire teams into either a PPG or HRG. Pair matching based on playing position was used for the same purpose, while also potentially achieving a balanced distribution of baseline characteristics as seen in both groups having a 1.2 ±0.2 kg/bw squat pre intervention as well as baseline descriptive statistics showing no significant differences (p=>0.005). Even though randomized controlled trials (RCTs) are considered the gold standard for evaluating the effectiveness of interventions, it is important to note that the results may not be generalizable to populations other than those studied (Hariton & Locascio, 2018). RCTs are typically designed to be conducted under highly controlled conditions, which can limit the external validity of the findings.

Subjects aware they're being studied are also prone to change behaviour confounding the real effect of the intervention, a phenomenon named the Hawthorne effect (McCambridge et al., 2014). Blinding was not possible in this study due to the nature of the interventions. Both the heavy load resistance training group and the power and plyometric training group required distinct exercises and training modalities that could not be concealed from the participants or trainers. As such, participants and trainers were aware of the training intervention they were receiving, which could potentially influence their expectations and motivation.

4.2 Participants

The inclusion of sub-elite female handball players in the study provided a relatively homogeneous sample with a certain level of physical fitness and athletic ability, which is important in reducing potential confounding factors in the intervention outcomes. However, caution must be taken when generalizing the results to other populations, particularly to elite female handball players, as their baseline characteristics, training status, and performance levels may differ significantly from those of the sub-elite players in the study. It is worth noting that both groups comprised relatively young individuals, with an average age of 19.5 years (HRG) and 20.4 years (PPG), respectively. This may limit the strength training status of several participants, possibly resulting in greater adaptions than those with a more extensive training background (This pronouncement was written for the American College of Sports Medicine by: William J. Kraemer et al., 2002).

4.3 Training intervention

Previous studies have shown significant adaptions from strength, power and plyometric training in interventions with durations of 8-12 weeks and 2-3 weekly sessions in female athletes (Falch et al., 2022; Pardos-Mainer et al., 2021). As such the present study's duration of 12 weeks with biweekly sessions is considered sufficient. There is a considerable challenge in matching the total volume of work to provide a similar stimulus when implementing heavy load resistance training vs power/plyometric in a training intervention. A 1:1 ratio of sets x repetitions cannot be assumed to achieve the same stimuli and the use of a higher total number of repetitions in the PPG group can help elicit a sufficient and comparable stimulus for both interventions (Grgic et al., 2021; Mohamad et al., 2012). The present study designed both training programs based on current best knowledge on what has shown training adaptions in previous studies. The use of similar movements with different loads, such as squat vs. squat jump, in the exercise selection also ensures adaptions are mainly influenced by the training modality (load and velocity) as opposed to the specific movement itself (This pronouncement was written for the American College of Sports Medicine by: William J. Kraemer et al., 2002). To ensure optimal stimuli and adaption to training interventions participants should be under the supervision of competent practitioners to ensure proper execution and progression. During the intervention one session a week was supervised by project members monitoring form, progression and intensity. Even though both sessions were not monitored, weekly supervising should be sufficient to ensure that the participants carried out the training program as required to get the intended adaptions. Subjects were also instructed to log every session via XPS Network. Progress and intensity were monitored using velocity feedback and RIR. Tracking velocity can be beneficial for ensuring maximal effort as well as estimating progress and load and is also shown to possibly increase adaptions during training interventions (Suchomel et al., 2021; Weakley et al., 2021). RIR can be effective in estimating intensity during high loads, especially with the addition of qualified supervision and velocity tracking (Helms et al., 2016). Power exercises were determined by percentage of 1RM, and velocity was tracked to ensure maximal effort. A limitation of the study is the difficulty of tracking velocity and/or RIR during certain exercises, both using sensor and observation, which possibly hinders proper intensity and effort during every exercise.

4.4 Measurements and test procedures

When investigating muscular adaptions to training stimuli, valid and reliable assessment methods as well as standardized testing procedures are vital to obtain quality data (Haun et al., 2019). Reliability refers to the consistency and repeatability of a test, while validity defines how well a test measures the specific aspect it is intended to investigate (Hopkins, 2000). Ensuring consistent testing conditions, such as using the same testing person, equipment and protocols, is important to maintain the reliability of the measures and were taken into account when establishing testing procedures. Both DXA, ultrasound and strength tests were performed by trained test members and done using the same equipment and protocol. Test-retest variability is also considered vital to ensure true observed changes in response to the intervention and was calculated as a coefficient of variation (CV%) for ultrasound and DXA. By assessing the test-retest variability the level of variability attributed to random error could be determined, as opposed to true differences in intervention effects.

4.4.1 Muscle morphology

Assessment of muscle tissue adaptions can, according to Haun et al, be divided into macroscopic and microscopic methods (Haun et al., 2019). Most exercise science studies use the macroscopic methods of muscle thickness and cross-sectional estimations from B-mode ultrasonography, computed tomography or magnetic resonance imaging or lean mass assessments from dual-energy X-ray absorbiometry, but microscopic methods such as muscle biopsies can be used as well (Grgic et al., 2021). While microscopic methods can give specific insights into muscular adaptions at the muscle fibre level, macroscopic methods are a practical and reliable method when you want to gain insight into adaptions on a total body or segmented muscle scale (Grgic et al., 2021). Skeletal muscle adaptions are not uniform and can occur at the distal, middle, or proximal area of different muscles, depending on the stimuli (EARP et al., 2015; Sarto et al., 2021). To capture the magnitude of adaptions it can be important to combine different measurement methods to assess specific muscles in different areas as well as total or segmented body parts (Haun et al., 2019). This present study therefore used the macroscopic methods of B-mode ultrasonography to assess muscle size and architecture as well as fat-free mass estimations from DXA. This should give sufficient data to assess macroscopic effects on muscle morphology.

4.4.1.1 DXA

Dual-energy x-ray absorptiometry is a widely used method to assess changes in skeletal muscle mass, and is generally considered a precise and reliable method for estimating body composition (Ackland et al., 2012; Haun et al., 2019; Kasper et al., 2021; Nana et al., 2015). The method produces images in 2D estimating bone mineral density (BMD), lean or fat-free mass (LBM/FFM) and fat mass. While DXA can provide estimates of total and segmented values of tissue, it is unable to distinguish between individual muscles or differentiate between muscle contractile tissue, fluid or intramuscular fat. It is therefore important to note that an increase in fat-free mass does not necessarily indicate an increase in skeletal muscle tissue. Measurements can be influenced by technical factors such as scan model, reference database, as well as biological factors such as subject preparation, age, sex and body size (Hind et al., 2018; Nana et al., 2015). The need for standardization and best practise protocol is therefore vital to obtain valid and reliable data (Nana et al., 2015). Nana et al 2015 discusses different measures in their paper regarding what is the best practise protocol to obtain quality data from DXA scans. While DXA as a whole is seen as a practical and non-invasive method that is easy to standardize, some measures for increased reliability can be difficult to accomplish due to the logistics and resources required. While the present study carried out the recommended measures of minimal clothing, trained test leaders, consistent positioning and voided bladder, morning testing in a fasted state was not possible due to logistics required and participants regular commitments (Nana et al., 2015). Participants were instructed to not eat a minimum of 2 hours pre-testing, which is not in accordance with best practice, as it could significantly impact the measurements. A test of reliability with the same protocol was performed at the same lab and machine and found good reliability with CV measures of 1% for FFM, 3.4 % for fat mass and 1.5 % for legs FFM. Furthermore, the testing was not conducted at a consistent time of day and early morning testing is recommended as daytime activities and nutrition intake can have a bigger impact on tests. Subjects were told not to exercise on testing days as it can impact test scores. While the method offers practical advantages and provides estimations of total and segmented lean mass, limitations regarding best practise procedure needs to be taken into account while interpreting the data.

4.4.1.2 Ultrasound

Ultrasound imaging was for assessing muscle thickness, cross-sectional area and pennation angle and is seen as a practical, affordable and non-invasive method for examining muscle morphology in athletes (Franchi et al., 2018; Sarto et al., 2021). B-mode ultrasonography, as used in this study, is the most commonly used ultrasound method for assessing muscle size and architecture. It allows differentiation between skeletal muscle, connective tissue and intra- and extramuscular fat, as well as estimation of fascicle length and pennation angle (Sarto et al., 2021). It has been proven valid and reliable in estimating muscle thickness, cross-sectional area and pennation angle of the muscles assessed (m. rectus femoris and m. vastus lateralis) (Kwah et al., 2013; Lixandrão et al., 2014; Sarto et al., 2021). The method still has its limitations being especially influenced by the skill of the investigator, and is therefore regarded as an operator depended procedure (Haun et al., 2019; Sarto et al., 2021). The majority of testing was performed by a novice test operator which could impact the reliability of the data. Sarto et al in their review from 2021, therefore recommends CV% to estimated and reported in the results (Sarto et al., 2021). Measures of CV ≤ 10% can be regarded as acceptable while CV ≤ 5% is regarded as good reliability (Lindberg et al., 2021). In the present study CV% was assessed from the familiarization session to baseline and while CSA and MT showed good of reliability (CV = 4-9%), measures of PA and FL was estimated at 20.3% and 21.6% respectively over the recommended limit of 10%. Even though using ultrasound for assessing muscle architecture has generally shown acceptable reliability (CV= <10%) in the literature, obtaining good images of muscle architecture was challenging due to the importance of getting the right angle for capturing visible individual fibres resulting in a smaller margin of error (Kwah et al., 2013). Pennation angel and fascicle length is known for often getting a higher CV estimate compared to MT and CSA and large variability up to CV 13.5%, as seen in the present study, has been reported in some studies (Kwah et al., 2013). This questions whether the presents study results from the muscle architecture can be used when assessing effects on PA and FL. Members were also not instructed to lay still for 20 minutes before taking images to account for shift in fluids, as done in Earp et al 2015 (EARP et al., 2015). In addition, the size of the probe was too small to fit the entire m. rectus femoris CSA in many of the images at the middle and proximal site. Therefore, a lot of images had to be analysed in a cut-off state or be extrapolated, impacting the precision and reliability of the analyses. The use of transparent sheets to locate measurements position is also prone to inaccuracy due to the curve of the muscle and lack of reference points (birthmarks, scars, moles) in some participants. Analysing of images can also be prone to bias when done manually, especially in novice test operators (Sarto et al., 2021). The use of automatic analysis in imageJ have been shown to reduce this bias, but we were not able to make it work for our images (Seynnes & Cronin, 2020). The images were therefore analysed manually in imageJ by a novice test operator increasing the risk for bias and error. To reduce bias images were blinded with regards to testing time (pre- vs post) and training group (HRG vs PPG). While ultrasound is a practical, valid and reliable measure method, limitations regarding testing operators' skill and experience as well as issues regarding testing procedures and data analyses must be taken into account when interpreting the data. It is as well only able to assess different muscles at specific sites possibly not detecting adaptions occurring elsewhere. This challenge is to a certain degree reduced by taking pictures at the proximal, middle and distal area of the muscles, as well as additional data from DXA. Overall measures of CSA and MT can be seen as reliable and should give a good assessment of muscle size adaptions.

4.4.2 Strength parameters

Monitoring of an individual’s strength characteristics is often done to establish an athlete’s baseline strengths and weaknesses or to evaluate acute and chronic training adaptions (Lindberg et al., 2022; McMaster et al., 2014). Maximal strength is an integral part of most sports and can be measured as maximal amount of force an athlete can produce against an external load in a specific movement (McMaster et al., 2014; Suchomel et al., 2016). It is therefore a useful quality to assess when profiling athletes physical qualities (McMaster et al., 2014). Assessing maximal strength can be done using dynamic tests such as 1-RM barbell testing (squat, benchpress) or isometric tests using force plates, dynamometers or strain gauges, in both single and multijoint movements (McMaster et al., 2014; Suchomel et al., 2016). Dynamic movements can potentially be seen as more relevant to a lot of athletes given that most sports express force dynamically. Measures of strength can be expressed in both absolute or relative terms (Suchomel et al., 2016). While measures from dynamic and isometric strength tests can be used to effectively assess strength development, they do not necessarily mirror sport specific strength requirements. In addition to choosing relevant tests for assessing maximal strength, any test needs to me considered valid and reliable to provide meaningful information regarding an athletes strength level and development (Redden et al., 2018). This present study use of a combination of dynamic and isometric strength testing, assessing 1-RM in squat and benchpress, Keiser leg press and an isometric MVC of knee extension should give a good assessment of athletes upper and lower body maximal strength.

4.4.2.1 1RM

One-repetition maximum(1RM) testing is one of the most commonly used methods for assessing dynamic maximal strength, and is considered the gold standard for use in non-laboratory settings (Grgic et al., 2020; McMaster et al., 2014; Seo et al., 2012; Suchomel et al., 2016). It is defined as the maximal weight that can be lifted in a specific movement with correct technique and has been shown to be reliable in assessing maximal strength when allowing proper warmup and familiarization regardless of muscle group and gender (Grgic et al., 2020; Seo et al., 2012; Suchomel et al., 2016). The present study's protocol included standardized warm-ups, lifting techniques (squat depth, grip width), rest periods, and 1RM attempts. Although standardization ensures that participants are tested using consistent criteria and facilitates comparisons between individuals, the expression of strength is highly specific to the characteristics of a given movement (depth, grip, range of motion). Participants who are familiar with the movements are more likely to demonstrate an accurate representation of their true maximal strength, owing to neural adaptations specific to the movement, as opposed to those with limited experience. (Grgic et al., 2020). This impacts their rate of development during initial stages and can lead to large variance in performance improvement. This study therefore employed a recommended familiarization period to reduce the effects of task learning and stabilize performance at baseline testing (Calder & Gabriel, 2007; Dias et al., 2005; Green et al., 2014; Seo et al., 2012). Squat depth was visually assessed which could influence whether every recorded lift was at required depth. Some subjects also found it difficult to squat at parallel due to lack of prior experience as well as mobility, which can lead to a reduced performance at baseline and subsequent large improvement in performance not related to the variables studied. Subjects were also not always assessed by the same test leader at pre- and post-testing which could lead to differences in evaluation of required depth. Overall, while the method has its limitations, the 1RM testing protocol of benchpress and squat employed should ensure valid and reliable measures when assessing maximal strength.

4.4.2.2 Keiser Leg press

Keiser Leg Press is a practical way of assessing strength and power characteristics of the lower limbs, including maximal strength, and has been demonstrated to be a reliable and valid method (Redden et al., 2018). The test is not technically demanding and is easy to standardize (Lindberg et al., 2022). The seated position with feet elevated, allows offloaded estimation of maximal concentric strength (Redden et al., 2018). While the seated position combined with low technical demands allows great expression of force, the relatability of the movement to sport specific movements can be questioned (Redden et al., 2018). Another possible limitation of the method, regarding maximal strength, is the pre-determined increments based on estimated maximum resistance, which may be unable to detect subtle changes in performance if the increment is too large. However, given the practicality of the method, combined with high measures of reliability, it is a valid and precise method to assess maximal strength.

4.4.2.3 MVC

Single-joint isometric testing of maximal strength is frequently used in sports science, owing to its versatility as well as its correlation with dynamic strength performance (Šarabon et al., 2021; Suchomel et al., 2016). Most research on single-joint strength assessment has been done on the knee joint, likely due to the high reliability of the strength measures and relevance of muscle groups for athletic performance. The majority of research on single-joint strength assessment has focused on the knee joint, which can be attributed to the high reliability of strength measurements and the relevance of the associated muscle groups for athletic performance (Šarabon et al., 2021). Isometric strength testing is easy to standardize and can also be conducted on large groups. The present study employed a standardized protocol, which incorporated consistent seating positions, dynamometer attachments, and knee angles which improves reliability. The bench platform featured handles on each side, designed to provide sufficient stability and facilitate optimal force output. Furthermore, the use of a dynamometer may obtain a more accurate expression of maximal strength compared to estimating maximal strength against an external load. (Suchomel et al., 2016). While the method has obvious strengths regarding practicality and reliability, one must keep in mind the sport specific demands when choosing joint angle (Suchomel et al., 2016). Knee extension at a 90° angle is considered relevant, given the significance of knee extensors in various sport-specific movements.

4.5 References

Abe, T., Fukashiro, S., Harada, Y., & Kawamoto, K. (2001). Relationship between sprint performance and muscle fascicle length in female sprinters. *Journal of Physiological Anthropology and Applied Human Science*, *20*(2), 141–147. https://doi.org/10.2114/jpa.20.141

Abe, T., Kumagai, K., & Brechue, W. F. (2000). Fascicle length of leg muscles is greater in sprinters than distance runners. *Medicine and Science in Sports and Exercise*, *32*(6), 1125–1129. https://doi.org/10.1097/00005768-200006000-00014

Ackland, T. R., Lohman, T. G., Sundgot-Borgen, J., Maughan, R. J., Meyer, N. L., Stewart, A. D., & Müller, W. (2012). Current status of body composition assessment in sport: Review and position statement on behalf of the ad hoc research working group on body composition health and performance, under the auspices of the I.O.C. Medical Commission. *Sports Medicine (Auckland, N.Z.)*, *42*(3), 227–249. https://doi.org/10.2165/11597140-000000000-00000

Andersen, L. L., & Aagaard, P. (2006). Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *European Journal of Applied Physiology*, *96*(1), 46–52. https://doi.org/10.1007/s00421-005-0070-z

Andersen, L. L., Andersen, J. L., Magnusson, S. P., Suetta, C., Madsen, J. L., Christensen, L. R., & Aagaard, P. (2005). Changes in the human muscle force-velocity relationship in response to resistance training and subsequent detraining. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, *99*(1), 87–94. https://doi.org/10.1152/japplphysiol.00091.2005

Arntz, F., Mkaouer, B., Markov, A., Schoenfeld, B. J., Moran, J., Ramirez-Campillo, R., Behrens, M., Baumert, P., Erskine, R. M., Hauser, L., & Chaabene, H. (2022). Effect of Plyometric Jump Training on Skeletal Muscle Hypertrophy in Healthy Individuals: A Systematic Review With Multilevel Meta-Analysis. *Frontiers in Physiology*, *13*. https://doi.org/10.3389/fphys.2022.888464

Beato, M. (2022). Recommendations for the design of randomized controlled trials in strength and conditioning. Common design and data interpretation. *Frontiers in Sports and Active Living*, *4*. https://www.frontiersin.org/articles/10.3389/fspor.2022.981836

Blazevich, A. J., Gill, N. D., Bronks, R., & Newton, R. U. (2003). Training-Specific Muscle Architecture Adaptation after 5-wk Training in Athletes. *Medicine & Science in Sports & Exercise*, *35*(12), 2013. https://doi.org/10.1249/01.MSS.0000099092.83611.20

Blazevich, A. J., Gill, N. D., & Zhou, S. (2006). Intra- and intermuscular variation in human quadriceps femoris architecture assessed in vivo. *Journal of Anatomy*, *209*(3), 289–310. https://doi.org/10.1111/j.1469-7580.2006.00619.x

Calder, K. M., & Gabriel, D. A. (2007). Adaptations during familiarization to resistive exercise. *Journal of Electromyography and Kinesiology*, *17*(3), 328–335. https://doi.org/10.1016/j.jelekin.2006.02.006

Chelly, M. S., Ghenem, M. A., Abid, K., Hermassi, S., Tabka, Z., & Shephard, R. J. (2010). Effects of in-Season Short-Term Plyometric Training Program on Leg Power, Jump- and Sprint Performance of Soccer Players. *The Journal of Strength & Conditioning Research*, *24*(10). https://journals.lww.com/nsca-jscr/Fulltext/2010/10000/Effects_of_in_Season_Short_Term_Plyometric.13.aspx

Cormie, P., McGuigan, M. R., & Newton, R. U. (2011a). Developing Maximal Neuromuscular Power. *Sports Medicine*, *41*(1), 17–38. https://doi.org/10.2165/11537690-000000000-00000

Cormie, P., McGuigan, M. R., & Newton, R. U. (2011b). Developing Maximal Neuromuscular Power. *Sports Medicine*, *41*(2), 125–146. https://doi.org/10.2165/11538500-000000000-00000

Cormier, P., Freitas, T. T., & Seaman, K. (2021). A systematic review of resistance training methodologies for the development of lower body concentric mean power, peak power, and mean propulsive power in team-sport athletes. *Sports Biomechanics*, 1–34. https://doi.org/10.1080/14763141.2021.1948601

Dias, R. M. R., Cyrino, E. S., Salvador, E. P., Caldeira, L. F. S., Nakamura, F. Y., Papst, R. R., Bruna, N., & Gurjão, A. L. D. (2005). Influence of familiarization process on muscular strength assessment in 1-RM tests. *Rev Bras Med Esporte*, *11*.

EARP, J. E., NEWTON, R. U., CORMIE, P., & BLAZEVICH, A. J. (2015). Inhomogeneous Quadriceps Femoris Hypertrophy in Response to Strength and Power Training. *Medicine & Science in Sports & Exercise*, *47*(11). https://journals.lww.com/acsm-msse/Fulltext/2015/11000/Inhomogeneous_Quadriceps_Femoris_Hypertrophy_in.18.aspx

Falch, H. N., Haugen, M. E., Kristiansen, E. L., & van den Tillaar, R. (2022). Effect of Strength vs. Plyometric Training upon Change of Direction Performance in Young Female Handball Players. *International Journal of Environmental Research and Public Health*, *19*(11), Article 11. https://doi.org/10.3390/ijerph19116946

Falch, H. N., Kristiansen, E. L., Haugen, M. E., & van den Tillaar, R. (2021). Association of Performance in Strength and Plyometric Tests with Change of Direction Performance in Young Female Team-Sport Athletes. *Journal of Functional Morphology and Kinesiology*, *6*(4), 83. https://doi.org/10.3390/jfmk6040083

Faude, O., Koch, T., & Meyer, T. (2012). Straight sprinting is the most frequent action in goal situations in professional football. *Journal of Sports Sciences*, *30*(7), 625–631. https://doi.org/10.1080/02640414.2012.665940

Folland, J., & Williams, A. (2007). The adaptations to strength training: Morphological and neurological contributions to increased strength. *Sports Medicine (Auckland, N.Z.)*, *37*, 145–168.

Franchi, M. V., Raiteri, B. J., Longo, S., Sinha, S., Narici, M. V., & Csapo, R. (2018). Muscle Architecture Assessment: Strengths, Shortcomings and New Frontiers of in Vivo Imaging Techniques. *Ultrasound in Medicine & Biology*, *44*(12), 2492–2504. https://doi.org/10.1016/j.ultrasmedbio.2018.07.010

Freitas, T., Calleja Gonzalez, J., Carlos-Vivas, J., Marín Cascales, E., & Alcaraz, P. (2018). Short-term optimal load training vs a modified complex training in semi-professional basketball players. *Journal of Sports Sciences*, *37*, 1–9. https://doi.org/10.1080/02640414.2018.1504618

Gabriel, D. A., Kamen, G., & Frost, G. (2006). Neural Adaptations to Resistive Exercise. *Sports Medicine*, *36*(2), 133–149. https://doi.org/10.2165/00007256-200636020-00004

García-Sánchez, C., Navarro, R. M., Karcher, C., & de la Rubia, A. (2023). Physical Demands during Official Competitions in Elite Handball: A Systematic Review. *International Journal of Environmental Research and Public Health*, *20*(4), Article 4. https://doi.org/10.3390/ijerph20043353

Green, L. A., Parro, J. J., & Gabriel, D. A. (2014). Quantifying the familiarization period for maximal resistive exercise. *Applied Physiology, Nutrition, and Metabolism*, *39*(3), 275–281. https://doi.org/10.1139/apnm-2013-0253

Grgic, J., Lazinica, B., Schoenfeld, B. J., & Pedisic, Z. (2020). Test–Retest Reliability of the One-Repetition Maximum (1RM) Strength Assessment: A Systematic Review. *Sports Medicine - Open*, *6*(1), 31. https://doi.org/10.1186/s40798-020-00260-z

Grgic, J., Schoenfeld, B. J., & Mikulic, P. (2021). Effects of plyometric vs. Resistance training on skeletal muscle hypertrophy: A review. *Journal of Sport and Health Science*, *10*(5), 530–536. https://doi.org/10.1016/j.jshs.2020.06.010

Handsfield, G. G., Knaus, K. R., Fiorentino, N. M., Meyer, C. H., Hart, J. M., & Blemker, S. S. (2017). Adding muscle where you need it: Non-uniform hypertrophy patterns in elite sprinters. *Scandinavian Journal of Medicine & Science in Sports*, *27*(10), 1050–1060. https://doi.org/10.1111/sms.12723

Hariton, E., & Locascio, J. J. (2018). Randomised controlled trials - the gold standard for effectiveness research: Study design: randomised controlled trials. *BJOG: An International Journal of Obstetrics and Gynaecology*, *125*(13), 1716. https://doi.org/10.1111/1471-0528.15199

Haun, C. T., Vann, C. G., Roberts, B. M., Vigotsky, A. D., Schoenfeld, B. J., & Roberts, M. D. (2019). A Critical Evaluation of the Biological Construct Skeletal Muscle Hypertrophy: Size Matters but So Does the Measurement. *Frontiers in Physiology*, *10*. https://www.frontiersin.org/articles/10.3389/fphys.2019.00247

Helms, E. R., Cronin, J., Storey, A., & Zourdos, M. C. (2016). Application of the Repetitions in Reserve-Based Rating of Perceived Exertion Scale for Resistance Training. *Strength and Conditioning Journal*, *38*(4), 42–49. https://doi.org/10.1519/SSC.0000000000000218

Henneman, E., Clamann, H. P., Gillies, J. D., & Skinner, R. D. (1974). Rank order of motoneurons within a pool: Law of combination. *Journal of Neurophysiology*, *37*(6), 1338–1349. https://doi.org/10.1152/jn.1974.37.6.1338

Henneman, E., Somjen, G., & Carpenter, D. O. (1965). FUNCTIONAL SIGNIFICANCE OF CELL SIZE IN SPINAL MOTONEURONS. *Journal of Neurophysiology*, *28*, 560–580. https://doi.org/10.1152/jn.1965.28.3.560

Hermassi, S., van den Tillaar, R., Khlifa, R., Chelly, M. S., & Chamari, K. (2015). Comparison of In-Season-Specific Resistance vs. A Regular Throwing Training Program on Throwing Velocity, Anthropometry, and Power Performance in Elite Handball Players. *The Journal of Strength & Conditioning Research*, *29*(8). https://journals.lww.com/nsca-jscr/Fulltext/2015/08000/Comparison_of_In_Season_Specific_Resistance_vs__A.5.aspx

Hopkins, W. G. (2000). Measures of Reliability in Sports Medicine and Science. *Sports Medicine*, *30*(1), 1–15. https://doi.org/10.2165/00007256-200030010-00001

Izquierdo, M., González-Badillo, J. J., Häkkinen, K., Ibáñez, J., Kraemer, W. J., Altadill, A., Eslava, J., & Gorostiaga, E. M. (2006). Effect of Loading on Unintentional Lifting Velocity Declines During Single Sets of Repetitions to Failure During Upper and

Lower Extremity Muscle Actions. *International Journal of Sports Medicine*, *27*(9), 718–724. https://doi.org/10.1055/s-2005-872825

Karcher, C., & Buchheit, M. (2014). On-Court Demands of Elite Handball, with Special Reference to Playing Positions. *Sports Medicine (Auckland, N.Z.)*, *44*. https://doi.org/10.1007/s40279-014-0164-z

Kasper, A. M., Langan-Evans, C., Hudson, J. F., Brownlee, T. E., Harper, L. D., Naughton, R. J., Morton, J. P., & Close, G. L. (2021). Come Back Skinfolds, All Is Forgiven: A Narrative Review of the Efficacy of Common Body Composition Methods in Applied Sports Practice. *Nutrients*, *13*(4), 1075. https://doi.org/10.3390/nu13041075

Komi, P. V. (1986). Training of muscle strength and power: Interaction of neuromotoric, hypertrophic, and mechanical factors. *International Journal of Sports Medicine*, *7 Suppl 1*, 10–15. https://doi.org/10.1055/s-2008-1025796

Kruse, A., Rivares, C., Weide, G., Tilp, M., & Jaspers, R. T. (2021). Stimuli for Adaptations in Muscle Length and the Length Range of Active Force Exertion—A Narrative Review. *Frontiers in Physiology*, *12*, 742034. https://doi.org/10.3389/fphys.2021.742034

Kumagai, K., Abe, T., Brechue, W. F., Ryushi, T., Takano, S., & Mizuno, M. (2000). Sprint performance is related to muscle fascicle length in male 100-m sprinters. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, *88*(3), 811–816. https://doi.org/10.1152/jappl.2000.88.3.811

Kwah, L. K., Pinto, R. Z., Diong, J., & Herbert, R. D. (2013). Reliability and validity of ultrasound measurements of muscle fascicle length and pennation in humans: A systematic review. *Journal of Applied Physiology*, *114*(6), 761–769. https://doi.org/10.1152/japplphysiol.01430.2011

Larsson, L., & Ansved, T. (1985). Effects of long-term physical training and detraining on enzyme histochemical and functional skeletal muscle characteristic in man. *Muscle & Nerve*, *8*(8), 714–722. https://doi.org/10.1002/mus.880080815

Lee, K.-L., Oh, T.-W., Gil, Y.-C., & Kim, H.-J. (2021). Correlation between muscle architecture and anaerobic power in athletes involved in different sports. *Scientific Reports*, *11*(1), Article 1. https://doi.org/10.1038/s41598-021-92831-7

Lieber, R. L. (2022). Can we just forget about pennation angle? *Journal of Biomechanics*, *132*, 110954. https://doi.org/10.1016/j.jbiomech.2022.110954

Lindberg, K., Solberg, P., Bjørnsen, T., Helland, C., Rønnestad, B., Frank, M. T., Haugen, T., Østerås, S., Kristoffersen, M., Midttun, M., Sæland, F., Eythorsdottir, I., & Paulsen,

G. (2022). Strength and Power Testing of Athletes: A Multicenter Study of Test–Retest Reliability. *International Journal of Sports Physiology and Performance*, *17*(7), 1103–1110. https://doi.org/10.1123/ijspp.2021-0558

Lindberg, K., Solberg, P., Bjørnsen, T., Helland, C., Rønnestad, B., Frank, M. T., Haugen, T., Østerås, S., Kristoffersen, M., Midttun, M., Sæland, F., & Paulsen, G. (2021). Force-velocity profiling in athletes: Reliability and agreement across methods. *PLOS ONE*, *16*(2), e0245791. https://doi.org/10.1371/journal.pone.0245791

Lixandrão, M. E., Ugrinowitsch, C., Bottaro, M., Chacon-Mikahil, M. P. T., Cavaglieri, C. R., Min, L. L., de Souza, E. O., Laurentino, G. C., & Libardi, C. A. (2014). Vastus Lateralis Muscle Cross-sectional Area Ultrasonography Validity for Image Fitting in Humans. *The Journal of Strength & Conditioning Research*, *28*(11), 3293. https://doi.org/10.1519/JSC.0000000000000532

Manchado, C., Tortosa-Martínez, J., Vila, H., Ferragut, C., & Platen, P. (2013). Performance Factors in Women's Team Handball: Physical and Physiological Aspects—A Review. *The Journal of Strength & Conditioning Research*, *27*(6), 1708. https://doi.org/10.1519/JSC.0b013e3182891535

McCambridge, J., Witton, J., & Elbourne, D. R. (2014). Systematic review of the Hawthorne effect: New concepts are needed to study research participation effects. *Journal of Clinical Epidemiology*, *67*(3), 267–277. https://doi.org/10.1016/j.jclinepi.2013.08.015

McMaster, D. T., Gill, N., Cronin, J., & McGuigan, M. (2014). A Brief Review of Strength and Ballistic Assessment Methodologies in Sport. *Sports Medicine*, *44*(5), 603–623. https://doi.org/10.1007/s40279-014-0145-2

Medler, S. (2019). Mixing it up: The biological significance of hybrid skeletal muscle fibers. *The Journal of Experimental Biology*, *222*, jeb200832. https://doi.org/10.1242/jeb.200832

Methenitis, S. K., Zaras, N. D., Spengos, K. M., Stasinaki, A.-N. E., Karampatsos, G. P., Georgiadis, G. V., & Terzis, G. D. (2016). Role of Muscle Morphology in Jumping, Sprinting, and Throwing Performance in Participants With Different Power Training Duration Experience. *The Journal of Strength & Conditioning Research*, *30*(3), 807–817. https://doi.org/10.1519/JSC.0000000000001147

Michalsik, L., & Aagaard, P. (2014). Physical demands in elite team handball: Comparisons between male and female players. *The Journal of Sports Medicine and Physical Fitness*, *55*.

Miller, R., Balshaw, T. G., Massey, G. J., Maeo, S., Lanza, M. B., Johnston, M., Allen, S. J., & Folland, J. P. (2021). The Muscle Morphology of Elite Sprint Running. *Medicine and Science in Sports and Exercise*, *53*(4), 804–815. https://doi.org/10.1249/MSS.0000000000002522

Mohamad, N. I., Cronin, J. B., & Nosaka, K. K. (2012). Difference in Kinematics and Kinetics Between High- and Low-Velocity Resistance Loading Equated by Volume: Implications for Hypertrophy Training. *The Journal of Strength & Conditioning Research*, *26*(1). https://journals.lww.com/nsca-jscr/Fulltext/2012/01000/Difference_in_Kinematics_and_Kinetics_Between.36.aspx

Moher, D., Schulz, K. F., & Altman, D. G. (2001). The CONSORT Statement: Revised Recommendations for Improving the Quality of Reports of Parallel-Group Randomized Trials. *Annals of Internal Medicine*, *134*(8), 657–662. https://doi.org/10.7326/0003-4819-134-8-200104170-00011

Myers, M. J., & Steudel, K. (1985). Effect of Limb Mass and its Distribution on the Energetic Cost of Running. *Journal of Experimental Biology*, *116*(1), 363–373. https://doi.org/10.1242/jeb.116.1.363

Nana, A., Slater, G. J., Stewart, A. D., & Burke, L. M. (2015). Methodology Review: Using Dual-Energy X-Ray Absorptiometry (DXA) for the Assessment of Body Composition in Athletes and Active People. *International Journal of Sport Nutrition and Exercise Metabolism*, *25*(2), 198–215. https://doi.org/10.1123/ijsnem.2013-0228

Pardos-Mainer, E., Lozano, D., Torrontegui-Duarte, M., Cartón-Llorente, A., & Roso-Moliner, A. (2021). Effects of Strength vs. Plyometric Training Programs on Vertical Jumping, Linear Sprint and Change of Direction Speed Performance in Female Soccer Players: A Systematic Review and Meta-Analysis. *International Journal of Environmental Research and Public Health*, *18*(2). https://doi.org/10.3390/ijerph18020401

Plotkin, D. L., Roberts, M. D., Haun, C. T., & Schoenfeld, B. J. (2021). Muscle Fiber Type Transitions with Exercise Training: Shifting Perspectives. *Sports*, *9*(9). https://doi.org/10.3390/sports9090127

Póvoas, S., Seabra, A., Ascensão, A., Magalhães, J., Soares, J., & Rebelo, A. (2012). Physical and Physiological Demands of Elite Team Handball. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *26*. https://doi.org/10.1519/JSC.0b013e318248aeee

Ramirez-Campillo, R., García-Pinillos, F., T. Nikolaidis, P., Clemente, F., Gentil, P., & García-Hermoso, A. (2022). Body composition adaptations to lower-body plyometric training: A systematic review and meta-analysis. *Biology of Sport*, *39*(2), 273–287. https://doi.org/10.5114/biolsport.2022.104916

Redden, J., Stokes, K., & Williams, S. (2018). Establishing the Reliability and Limits of Meaningful Change of Lower Limb Strength and Power Measures during Seated Leg Press in Elite Soccer Players. *Journal of Sports Science & Medicine*, *17*(4), 539–546.

Sammoud, S., Bouguezzi, R., Ramirez-Campillo, R., Negra, Y., Prieske, O., Moran, J., & Chaabene, H. (2022). Effects of plyometric jump training versus power training using free weights on measures of physical fitness in youth male soccer players. *Journal of Sports Sciences*, *40*(2), 130–137. https://doi.org/10.1080/02640414.2021.1976570

Sánchez, M., Sanchez-Sanchez, J., Nakamura, F. Y., Clemente, F. M., Romero-Moraleda, B., & Ramirez-Campillo, R. (2020). Effects of Plyometric Jump Training in Female Soccer Player's Physical Fitness: A Systematic Review with Meta-Analysis. *International Journal of Environmental Research and Public Health*, *17*(23). https://doi.org/10.3390/ijerph17238911

Šarabon, N., Kozinc, Ž., & Perman, M. (2021). Establishing Reference Values for Isometric Knee Extension and Flexion Strength. *Frontiers in Physiology*, *12*. https://www.frontiersin.org/articles/10.3389/fphys.2021.767941

Sarto, F., Spörri, J., Fitze, D. P., Quinlan, J. I., Narici, M. V., & Franchi, M. V. (2021). Implementing Ultrasound Imaging for the Assessment of Muscle and Tendon Properties in Elite Sports: Practical Aspects, Methodological Considerations and Future Directions. *Sports Medicine*, *51*(6), 1151–1170. https://doi.org/10.1007/s40279-021-01436-7

Schoenfeld, B. J. (2010). The Mechanisms of Muscle Hypertrophy and Their Application to Resistance Training. *The Journal of Strength & Conditioning Research*, *24*(10), 2857. https://doi.org/10.1519/JSC.0b013e3181e840f3

Schoenfeld, B. J., Grgic, J., Ogborn, D., & Krieger, J. W. (2017). Strength and Hypertrophy Adaptations Between Low- vs. High-Load Resistance Training: A Systematic Review and Meta-analysis. *Journal of Strength and Conditioning Research*, *31*(12), 3508–3523. https://doi.org/10.1519/JSC.0000000000002200

Semmler, J. g., & Enoka, R. m. (2000). Neural Contributions to Changes in Muscle Strength. In *Biomechanics in Sport* (pp. 2–20). John Wiley & Sons, Ltd. https://doi.org/10.1002/9780470693797.ch1

Seo, D., Kim, E., Fahs, C. A., Rossow, L., Young, K., Ferguson, S. L., Thiebaud, R., Sherk, V. D., Loenneke, J. P., Kim, D., Lee, M., Choi, K., Bemben, D. A., Bemben, M. G., & So, W.-Y. (2012). Reliability of the One-Repetition Maximum Test Based on Muscle Group and Gender. *Journal of Sports Science & Medicine*, *11*(2), 221–225.

Seynnes, O. R., & Cronin, N. J. (2020). Simple Muscle Architecture Analysis (SMA): An ImageJ macro tool to automate measurements in B-mode ultrasound scans. *PLoS ONE*, *15*(2), e0229034. https://doi.org/10.1371/journal.pone.0229034

Simoneau, J. A., & Bouchard, C. (1995). Genetic determinism of fiber type proportion in human skeletal muscle. *FASEB Journal: Official Publication of the Federation of American Societies for Experimental Biology*, *9*(11), 1091–1095. https://doi.org/10.1096/fasebj.9.11.7649409

Slimani, M., Chamari, K., Miarka, B., Del Vecchio, F. B., & Chéour, F. (2016). Effects of Plyometric Training on Physical Fitness in Team Sport Athletes: A Systematic Review. *Journal of Human Kinetics*, *53*, 231–247. https://doi.org/10.1515/hukin-2016-0026

Stolen, T., Chamari, K., Castagna, C., & Wisloff, U. (2005). Physiology of Soccer. *Sports Medicine (Auckland, N.Z.)*, *35*, 501–536. https://doi.org/10.2165/00007256-200535060-00004

Suchomel, T. J., Nimphius, S., Bellon, C. R., Hornsby, W. G., & Stone, M. H. (2021). Training for Muscular Strength: Methods for Monitoring and Adjusting Training Intensity. *Sports Medicine*, *51*(10), 2051–2066. https://doi.org/10.1007/s40279-021-01488-9

Suchomel, T. J., Nimphius, S., Bellon, C. R., & Stone, M. H. (2018). The Importance of Muscular Strength: Training Considerations. *Sports Medicine*, *48*(4), 765–785. https://doi.org/10.1007/s40279-018-0862-z

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The Importance of Muscular Strength in Athletic Performance. *Sports Medicine*, *46*(10), 1419–1449. https://doi.org/10.1007/s40279-016-0486-0

Taber, C., Bellon, C., Abbott, H., & Bingham, G. E. (2016). Roles of Maximal Strength and Rate of Force Development in Maximizing Muscular Power. *Strength & Conditioning Journal*, *38*(1), 71. https://doi.org/10.1519/SSC.0000000000000193

This pronouncement was written for the American College of Sports Medicine by: William J. Kraemer, P. D., Kent Adams, P. D., & Enzo. (2002). Progression Models in

Resistance Training for Healthy Adults. *Medicine & Science in Sports & Exercise*, *34*(2), 364.

Timmins, R. G., Shield, A. J., Williams, M. D., Lorenzen, C., & Opar, D. A. (2016). Architectural adaptations of muscle to training and injury: A narrative review outlining the contributions by fascicle length, pennation angle and muscle thickness. *British Journal of Sports Medicine*, *50*(23), 1467–1472. https://doi.org/10.1136/bjsports-2015-094881

Travis, S. K., Ishida, A., Taber, C. B., Fry, A. C., & Stone, M. H. (2020). Emphasizing Task-Specific Hypertrophy to Enhance Sequential Strength and Power Performance. *Journal of Functional Morphology and Kinesiology*, *5*(4), 76–0. https://doi.org/10.3390/jfmk5040076

Turner, A. N., & Jeffreys, I. (2010). The Stretch-Shortening Cycle: Proposed Mechanisms and Methods for Enhancement. *Strength & Conditioning Journal*, *32*(4), 87. https://doi.org/10.1519/SSC.0b013e3181e928f9

Van Cutsem, M., Duchateau, J., & Hainaut, K. (1998). Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *The Journal of Physiology*, *513 (Pt 1)*(Pt 1), 295–305. https://doi.org/10.1111/j.1469-7793.1998.295by.x

Wagner, H., Gierlinger, M., Adzamija, N., Ajayi, S., Bacharach, D. W., & von Duvillard, S. P. (2017). Specific Physical Training in Elite Male Team Handball. *Journal of Strength and Conditioning Research*, *31*(11), 3083–3093. https://doi.org/10.1519/JSC.0000000000002094

Weakley, J. J. S., Till, K., Read, D. B., Leduc, C., Roe, G. A. B., Phibbs, P. J., Darrall-Jones, J., & Jones, B. (2021). Jump Training in Rugby Union Players: Barbell or Hexagonal Bar? *Journal of Strength and Conditioning Research*, *35*(3), 754–761. https://doi.org/10.1519/JSC.0000000000002742

Wisløff, U., Castagna, C., Helgerud, J., Jones, R., & Hoff, J. (2004). Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *British Journal of Sports Medicine*, *38*(3), 285–288. https://doi.org/10.1136/bjsm.2002.002071

PART 2

RESEARCH PAPER

Go heavy or go home?

In-season heavy load resistance training vs power/plyometric training on muscle size, architecture and strength in female handball players

The following paper is written according to the standards of the journal:

Scandinavian Journal of Medicine & Science in Sports

Simon Aune

University of Agder

May 2023

Abstract

Purpose: This study investigated the effects of in-season heavy-load resistance training vs power and plyometric training on muscle size-, architecture and strength, in female sub-elite handball players.

Methods: Thirty-one participants from two senior teams were randomized into a heavy-load resistance group (HRG; n=16, 19.5±2.8yrs, 169.9±6,2cm, 70.2±13.9kg) or a power/plyometric group (PPG; n=15, 20.4±2.8yrs, 170.4±5.9cm, 65.6±6.8kg). In biweekly sessions HRG performed 2-6 sets at 80-85% 1RM, while PPG performed 2-4 sets of power-exercises at ≤50% 1RM with 75-90 plyometric bodyweight jumps. Pre and post the 12-week intervention, fat-free mass (FFM) and maximal strength were assessed by Dual-X-Ray-Absorptiometry, one repetition maximum (1RM), isometric strength (MVC) and Leg Press pneumatic resistance force (Fmax). Muscle thickness (MT) and cross-sectional area (CSA) were obtained by ultrasonography from rectus femoris (RF) and vastus lateralis (VL) at the distal, middle and proximal thigh region. Pennation angle (PA) and fascicle length (FL) were assessed at VL middle region.

Results:FFM increased similarly in both groups. Between group %change was found in middle RF-CSA and middle VL-MT favouring HRG. PPG increased distal RF-CSA. HRG increased distal VL-MT and middle VL-MT. No change was found on pennation angle or fascicle length. HRG increased more in 1RM, but no between group difference was found in Fmax or MVC. HRG increased all strength measures, while PPG increased 1RM squat and MVC.

Conclusion: Both groups increased FFM, but muscle size of VL and RF showed non-homogenous effects between groups with greater effect in HRG. HRG also showed greater effect on maximal strength.

Keywords: Strength training, handball, muscle size, muscle architecture, muscle strength, female, in-season

Introduction

An athlete’s ability to produce high amounts of force at different velocities is regarded as a decisive factor for performance in team-sport.[1,2] Depending on the individuals' sport-specific tasks, force has to be generated rapidly, maximally, or repeatedly.[2] This holds especially true for handball, a rigorous contact sport that involves a multitude of fast, intense and dynamic actions, including jumping, sprinting, throwing, and engaging in duels. These activities in handball result in considerable requirements for force production. [3,4] A limiting factor and prerequisite for generating force is an athlete’s muscular strength both maximal and explosive, which in turn is strongly determined by the neural system and muscle size .[5,6] A larger muscle contains more contractile material, giving it more force producing potential, but the muscle fibre type, fascicle length and pennation angle of the contractile fibres will modulate the expression of this force.[5]

To enhance force production, handball players have used various training methods in-season, but the effects on muscle architectural characteristics differs based on the training method used. [7] Traditionally heavy load low velocity resistance training has been seen as the most effective for increasing structural adaptions such as muscle size compared with lower load high velocity training, and since muscle size is a determining factor for force production, heavy resistance training has therefore been used extensively in team-sport athletes. [8–11] Power and plyometric training has been seen as mainly a supplemental tool for improving neurological factors to increase force production at higher velocities but used in isolation considered as providing too small of a stimulus to maintain or increase muscle size and maximal strength.[6,11,12]

A recent review from 2021 by Grgic et al, challenges this perception by looking at studies comparing heavy load resistance training vs. plyometric training in the same cohort, rather than assessing the effects from individual studies.[10] They found similar effects on whole muscle hypertrophy on the lower extremities, although in mostly untrained participants. The magnitude of each adaption can depend on the exercise modality and different regional adaptions in hypertrophy have also been reported.[13–15] In a study by Earp et al. (2015) heavy squat vs. low-load squat jump resulted in similar increases of overall CSA of the quadricep femoris, but inhomogeneous adaptions at the proximal, middle and distal sites. [13] This is thought to be a consequence of region specific muscular demands between higher load and low velocity vs. lower load and high velocity movements resulting in regional muscle size adaptions, as well as specific architectural adaptions of pennation angle, fascicle length and fibre type. [5,10,13,16] Muscle fibres attaching with a large pennation angle will have a relatively higher physiological cross-sectional area and shorter fascicle length, and therefore more relative maximal force-production potential at lower velocity, while longer fascicle lengths and smaller pennation angle increases the number of sarcomeres arranged in series being more effective at high velocities.

Overall, this raises the question of whether power and plyometric training have a greater muscle architectural effect than previously though stimulating both neural and structural adaptions more specific to high movement velocities. Power and plyometric training may therefore be considered an effective in-season training program in isolation for team-sport athletes needing to produce high force at high velocities. [1,4,10,12,17,18] However, many team-sports already involve a large number of explosive actions, and these athletes might not respond to any additional power/plyometric training.[1,2] It could also compromise their ability to produce force maximally which is considered vital for their sport. These athletes may need a high load stimulus to further develop their force production, but this type of training typically demands more recovery time and could hinder their capacity to perform optimally in handball related activities. [1]

There is a lack of direct comparisons between these training modalities in isolation, especially in female team sport athletes, suggesting an area in need of further investigation. The purpose of this article will therefore be to investigate the effects of in-season heavy resistance training vs. power and plyometric training on muscle strength, -size and -architecture on female handball players.

Material and methods

Participants

Female handball players were recruited from two local senior teams (n=34) during the spring of 2022. Subjects at sub-elite level from the age of 16-35 years with prior strength training experience were included. Players with current injuries that would limit their performance during the training intervention and testing, or those who were pregnant, were excluded from the study. One player dropped out pre-intervention after being randomized into PPG. Two players dropped out during the training intervention due to injury and motivation respectively, resulting in a total of 31 participants which completed the study. A total of 31 female sub-elite handball players (age 20±2.78 years, height 170±5.95 cm, weight 68±11.1 kg) were randomized into a heavy load resistance group (heavy-load; n=16) and power and plyometric group (power-plyo; n=15). Baseline characteristics are presented in the following table (Table 1).

Table 1: Baseline characteristics

Group	Heavy load	Power-Plyo
Sample size (n)	16	15
Age	19.5±2.8	20.4±2.8
Weight	70.2±13.9	65.6±6.8
Height	169.9±6.2	170.4±5.9

Note: Values are presented as mean ± SD. Cm, centimeter; Kg, kilograms; SD, standard deviation.

Subjects received information about the study both in written and oral form (appendix X). Participation was voluntary and subjects could withdraw at any point. Written consent was obtained prior to testing. The study was approved by the ethical board of the faculty of sports science and physical education at the University of Agder (appendix Y), and the Norwegian Centre for Research Data (appendix XY) and was conducted in agreement with the Declaration of Helsinki.

Study design

This study was performed as a non-blinded randomized controlled trial (RCT) in which female handball players from two teams were assigned to either a heavy load resistance training group (HRG) or a power and plyometric training group (PPG) after baseline testing. Randomization into two groups was performed in both teams by pair matching based on playing position to reduce selection bias, ensure comparable baseline characteristics and exposure to similar physical demands during the season. Blinding was not possible due to the nature of the intervention. Prior to baseline testing, each group underwent a familiarization period for testing procedures to minimize task learning effects and improve the reliability of the assessments.

At baseline body composition and muscle architecture were assessed using dual-energy X-ray absorptiometry (DXA) scans and ultrasonography. DXA scans were used to measure fat-free mass and Ultrasonography was used to assess muscle architecture, including muscle thickness, cross-sectional area, fascicle length, and pennation angle. Muscle strength was assessed by testing 1RM parallel squat, 1RM benchpress, Keiser leg press (absolute and relative) and isometric maximum voluntary contraction (MVC) in knee extension.

Testing procedures

DXA

Dual-Energy X-ray absorptiometry (DXA) (GELunar Prodigy, General Electric Company, Madison, Wisconsin, USA) was used to assess total body and leg fat-free mass. Testing was performed by trained members of the research project. Height and weight were measured before the DXA scan using a mobile floor weight (Seca 877) and an altimeter (Seca 216), respectively. Subjects were instructed to fast at least 2 hours prior to the scan. Calibration was performed ahead of each day of testing according to the manufacturer's guidelines. Images were analysed using encore software (version 14.10.022; GE-Healthcare).

Ultrasound

Muscle thickness, pennation angle and fascicle length of m. vastus lateralis and muscle thickness and cross-sectional area of m. rectus femoris was assessed by ultrasonography (Telemed ArtUS EXT-1H, IT, 70 Hz, Vilnius, Lithuania: probe LV8-5N60-A2, 60mm). Subjects were instructed to lay relaxed on the massage table with their knee extended 180 degrees. The muscle thickness and cross-sectional area (CSA) measurements were taken directly between the hip and knee joint at the 33%, 50% and 67% at the femur length between the greater trochanter and lateral epicondyle of the femur, similar to Earp et al, 2015.[13], while muscle architecture was assessed approximately at the 50% position. Measuring sites were located by palpating and measuring tape, and all measurements were performed on the preferred jump leg. To ensure consistent measurement location, probe measurement positions were marked with a waterproof pen during the familiarization session and subsequently transferred onto a transparent sheet using moles, birthmarks, and scars as reference points. Measurement positions were then located during the pre-and post-tests by referencing the markings on the thigh from the transparent sheet and comparing them with previous images taken at the same location. After covering the probe with water-soluble transmission gel (Aquasonic 100 ultrasound transmission gel; Parker laboratories inc., Fairfield, NJ, USA), it was gently placed against the skin to not cause errors in measurements by excessive pressure [19,20]. Two trained test leaders performed the ultrasound measurements. The probe was held across the direction of the respective muscle fibers to capture images of muscle thickness and CSA, while it was held parallel with the fibers of m. vastus lateralis to assess muscle architecture. Images were saved and then later analysed manually using ImageJ (Wayne Rasband, National Institutes of Health, Bethesda/MD, USA). Muscle thickness was measured by drawing a vertical line between at the upper and deeper *aponeurosis* at positions determined by recognizable reference points (such as connective tissue and the femur bone) to ensure measurements were taken at the same place pre- and post-intervention. CSA was measured by using the freehand function to draw lines around the inside of the *aponeurosis.* Due to the size of the m. rectus femoris of a lot of the subjects, several pictures taken at the 50% and 67% sites could not fit entirely within the view of the probe. Therefore, reference points or a given distance from where the muscle thickness was measured were used to extrapolate or cut the images at the sides. To determine the pennation angle, a manual angle function was used to measure the angle of visible muscle fibers relative to the average direction of the deeper aponeurosis. Fascicle lengths were then estimated using average pennation angle (2-3) and average muscle thickness (measured at three points) put into the formula muscle thickness/(sinus(pennation angle* π)/180))

1 repetition maximum (1RM)

To assess both lower and upper body maximal strength, estimations of 1 repetition maximum (1RM) for parallel squats and bench press were performed respectively. For squats, subjects were instructed to achieve a depth where the top of the thighs were parallel to the ground, under the supervision of test leaders. A familiarization period allowed subjects to estimate their 1RM, which they sought to improve during baseline testing. The testing protocol began with 5 reps at 50% of the estimated 1RM, followed by 2-3 reps at 70% 1RM, and 1-2 reps at 90%. Then, 2-3 1RM attempts at a given load were undertaken. The loads were incrementally increased upon successful 1RM attempts until a weight could no longer be lifted or the successful attempt was near failure. For the bench press, the 1RM was part of a power profile, yet only the 1RM was utilized in this study. Subjects were instructed to use a traditional width grip, slightly wider than the shoulders, and to ensure the barbell touched the chest. The warm-up began with the barbell at 1-5 reps with increasing velocity. Subjects gradually increased their load towards 90% 1RM, with measurements taken at a minimum of 5 different loads preceding the 1RM testing. For both exercises, rest periods lengthened in accordance with heavier loads, ranging from 1-3 minutes.

Keiser leg press

A Keiser A300 seated pneumatic leg press machine was used to assess maximal strength in the lower limbs as absolute force (newton), estimated from a 10-repetition FV test pre-programmed in the Keiser software. The test starts at approximately 15% 1RM followed by incremental increase loads based on a 1 RM estimate obtained at familiarization. The seating position was set at ~90˚ knee angle aiming for a vertical femur with adjusted seating settings noted and used at pre- and post-test. Subjects were instructed to push with maximal effort and intent during the initial concentric push while not resisting during the eccentric part of the movement. The test was performed until muscular failure and 1RM was obtained. Rest periods (10-60 seconds) increased as the loads increased. The FV test used measures several aspects of force and velocity, such as peak force, velocity and power, but this present study will only use the 1RM measure for further analysis.[21]

MVC

An isometric maximum voluntary contraction of knee extensors was performed to assess maximal strength of the dominant jump leg. The test was performed at 90˚ knee angle sitting at bench platform with handles at each side with the back of the knee touching the edge of the bench. A force cell was attached to the ankle and attachments positions were noted for use at pre- and post-test. Warmup consisted of subjects pushing at 50-, 70- and 90% maximum force for 2-3 seconds with a 30 second rest period. Following a 1 min break, subjects were told to push as hard as they could for a period of 3-5 seconds. Each subject got 3 attempts with >30 second rest period. If recording the best attempt at the last rep, one more attempt was given. MVC was measured using a force cell (1000hz) from Musclelab (Ergotest Innovation, Stathelle, Norway).

Training intervention

The 12-week training intervention consisted of two weekly sessions (A and B) for both groups. Sessions A (high volume) and B (low volume) differed in their total volume, with the goal of facilitating easier implementation and timing of the training sessions to align with match days during the season. One session per week, usually session A, was supervised by project members to ensure that proper form, technique and progression were maintained during the training. Lifting velocity was tracked using VmaxPro® (Blaumann & Meyer, Sports Technology UG, Magdeburg, Germany; VMP) sensors to measure and ensure correct load and effort. Since the players were not familiar with using RIR, we measured velocity loss during squats in the HRG during the initial weeks to ensure the players were close to failure (velocity of <0.4 m/s at ~1RIR.[22] Participants in PPG were instructed to give maximal effort and minimize loss of velocity with visual and verbal feedback. For the push jerk exercise, the initial weeks were used to find a load that ensured a minimum of 1 m/s, this load was then maintained throughout the intervention. The heavy load resistance program involved performing 2-6 sets of exercises at intensities of approximately 80-85% of 1RM, while the power and plyometric groups performed 2-4 sets of power exercises at lower intensities of ≤50% 1RM, in combination with 75-90 plyometric bodyweight jumps. HRG and PPG training programs differ in total repetitions due to the different characteristics of each training modality. There is no consensus on how to match programs in terms of stimuli and overall workload so each program is based on current best knowledge on what has shown training adaptions in previous studies aiming for an optimal stimulus in both groups. XPS Network (Sideline Sports US LLC, Reykjavik, Iceland) was used for monitoring the participants during the intervention with players reporting sessions completed. Week 1 was performed as a familiarization period with reduced intensity (2-3RIR), effort (80-90% effort) and volume (2 sets), before performing the full training program from week 2.

Table 2: Heavy load training program

Session A				
Exercises	**Sets**	**Reps**	**Rest**	**RIR/intensity**
Parallel squat	3	5	3 min	1RIR
Split squat	3	5	3 min	1 RIR
Superset: hip thrust	3	5	3 min	1 RIR
Superset: one leg calf rise	3	10	2 min	High
Romanian deadlift	2	5	3 min	1 RIR
Superset: bench press	3	5	3 min	1 RIR
Superset: pullups/pulldowns	3	5	2 min	1 RIR
Shoulder press bar or dumbbells	2	5	2 min	1 RIR
Weighted sit-ups	2	10	2 min	High
Session B				
Parallel squat	2	5	3 min	1 RIR
Superset: nordic hamstring curl	2	5	3 min	High
Superset: superman/rollouts	2	10	2 min	High
Bulgarian lunges	2	5	3 min	1 RIR
Bench press with dumbbells	2	5	3 min	1 RIR
Superset: cable row or 1 – arm dumbbell rows	2	5	2 min	1 RIR
Superset: Triceps dumbbell press	2	5	2 min	1 RIR

Table 3: Power-plyo training program

Session A				
Exercises	**Sets**	**Reps**	**Rest**	**RIR/intensity**
Squat jump	4	5	3 min	50% 1RM
Push jerk	3	5	2 min	Velocity
Superset: Explosive bench press with elastic bands	3	5	2 min	50% 1RM
Superset: Single leg hip thrust jump	3	5	3 min	BW/max
Drop jump	3	10	2 min	BW/max
Superset: Kettlebell swing	3	8		12 kg +
Superset: Medicine ball chest throw	3	5	2 min	2-4 kg
Superset: Bulgarian jumps	3	5	3 min	BW/max
Superset: Box jumps	3	10	2 min	BW/max
Reverse rowing/med-ball slam	3	5	2 min	BW/max
Session B				
Squat jump	3	5	3 min	50% 1RM
Superset: Single leg hip thrust jump	2	5	2 min	BW/max
Superset: Medicine ball chest throw	2	5	2 min	2-4 kg
Hurdle jumps	2	10	2 min	BW/max
Split squat jumps	3	5	3 min	BW/max
Horizontal jumps	2	5	2 min	BW/max
Superset: Box jumps	2	10	2 min	BW/max
Superset: Reverse rowing	2	5	2 min	BW/max

Note: new exercises included in weeks 6-12

Statistical analysis

To assess whether the data were normally distributed, a Shapiro-Wilk test was conducted as well as an examination of the mean, median, skewness, kurtosis, and Q-Q. All data, except for PPG changes in body weight, squat, and MVC, were determined to be normally distributed. An independent samples t-test was used to evaluate between-group differences in percentage change from baseline, in addition to a Mann-Whitney U test for non-normally distributed data. To assess within-group changes from pre- to post-test, a paired samples t-test and Wilcoxon signed-rank test were performed. A significance level was established at $p < 0.05$, and confidence limits were set at 95%. Statistical analyses were conducted using Jamovi (2022, Version 2.3, the Jamovi project, Sydney, Australia). Descriptive baseline characteristics are presented as mean values and standard deviations (SD). Muscle size and strength results are reported as mean, percentage change, effect sizes (ES), SDs, confidence intervals, coefficients of variation (CV), and p-values. The effect size (ES) was calculated using Cohen's d.

Results

Between- and within-group pre-post absolute and relative changes and effect sizes for body composition, muscle morphology, and strength are presented in Table 5-7. Percent within-group changes from baseline in each variable are depicted in Figure 1. There was no significant difference in BW change between groups (P = 0.075) or change from baseline in both HRG and PPG (0.99% ± 2.04; P = 0.093 and -0.2% ± 2.7; P = 1.000) . TB-FFM showed no significant between-group difference (0.84%; P = 0.309) with significant increase from baseline in both HRG (2.53% ± 2.03%; ES: 1.24; P = < .001) and PPG (1.67% ± 2.49%; ES: 0.69; P = 0.018). L-FFM also showed no significant group-differences (1.35%; P = 0.256) with significant increase from baseline in HRG (4.05% ± 2.75%; ES: 1.40; P = < .001) and PPG (2.72% ± 3.67%; ES:0.73; P = 0.014).

Table 4: Body composition results

Change from baseline								**Between group percentage change differences**		
Variables and groups	N	Pre-test Mean ± SD	Post-test Mean ± SD	Δ% ± SD	95% CI (LB, UB)	_p_-value	Effect size	Mean (%)	95% CI (LB, UB)	_p_-value
Bodyweight (kg)										
HRG	16	70.2 ± 13.9	70.80 ± 13.60	0.99 ± 2.04	[-0.12, 1.40]	_0.093_	0.45	1.16	[-0.13, 2.50]	_0.075_
PPG	15	65.65 ± 6.8	65.65 ± 8.20	-0.20 ± 2.70	[-1.06, 1.06]	_1.000_	0.00			
FFM total (kg)										
HRG	16	49.81 ± 5.54	51.1 ± 6.08	2.53 ± 2.03	[0.74, 1.85]	_< .001_*	1.24	0.845	[-0.82, 2.52]	_0.309_
PPG	15	47.27 ± 4.08	48.07 ± 4.44	1.67 ± 2.49	[0.16, 1.44]	_0.018_*	0.69			
FFM legs (kg)										
HRG	16	17.13 ± 2.45	17.83 ± 2.59	4.05 ± 2.75	[0.43, 0.96]	_< .001_*	1.40	1.350	[-1.03, 3.73]	_0.256_
PPG	15	16.02 ± 1.71	16.45 ± 1.93	2.72 ± 3.67	[0.10, 0.77]	_0.014_*	0.73			

Abbreviations: HRG: Heavy-load resistance group, PPG: Power-Plyo Group, FFM: Fat-free mass, CI: Confidence interval, LB: lower bound, UB: Upper bound, ES: Effect size (Cohens D), KG:kilogram

RF-MT showed no significant difference in change between groups at any site (P=>0.05). Change from baseline was only seen in the proximal region with significant reductions in both HRG and PPG (-2.6% ± 3.2%; ES: -0.93; P = 0.003 vs. -2.1% ± 2.6%; ES: -0.6; P = 0.037). RF-CSA only showed between-group difference at the middle site (4.165%; P = 0.027) favouring HRG but change from baseline was not significant in any group (HRG: 3.0% ± 5.3%; ES: 0.5; P = 0.062 and PPG: -1.1% ± 4.5%; ES: -0.18; P = 0.49). RF-CSA increased significantly from baseline only in the distal region in PPG (4.3% ± 7.8%; ES: 0.58; P = 0.040) but showed no significant difference in between group percent change (1.56%; P = 0.634). Between group difference in VL-MT was only found at the middle site (3.149%; P =0.011) with significant increase from baseline only in HRG (HRG: 3.6% ± 3.5%; ES: 1.09; P = <.001 vs. PPG: 0.1% ± 3.4%; ES: 0.11; P = 0.665). VL-MT also increased significantly only in the distal region of the HRG (HRG: 3.8% ± 5.2%; ES: 0.79; P = 0.006 and PPG: 1.5% ± 4.5%; ES: 0.28; P = 0.292) but showed no significant between-group difference (2.249%; P = 0.210). No significant changes from baseline or between group percent change was found on pennation angle or fascicle length.

Table 5: Muscle size results

		Change from baseline							Between group differences		
		Pre-test	Post-test								
Variables and groups	n	Mean ± SD	Mean ± SD	Δ% ± SD	95% CI (LB, UB)	*p*-value	ES	CV	Mean (%)	95% CI (LB, UB)	*p*-value
Muscle thickness (mm)											
RF Distal											
HRG	16	20.3 ± 3.19	20.7 ± 3.03	2.6 ± 6.8	[-0.31,1.19]	*0.228*	0.31	5.8	1.211	[-3.82, 6.24]	*0.626*
PPG	15	19.9 ± 2.96	20.0 ± 2.36	1.4 ± 6.9	[-0.46, 0.80]	*0.567*	0.15				
RF Middle											
HRG	16	25.0 ± 2.38	25.1 ± 2.17	1.1 ± 4.4	[-0.41, 0.76]	*0.537*	0.16	5.2	-3.197	[-7.81, 1.42]	*0.167*
PPG	15	24.5 ± 1.76	24.2 ± 1.72	-1.2 ± 4.0	[-0.89, 0.38]	*0.399*	-0.22				
RF Proximal											
HRG	15	29.3 ± 2.53	28.5 ± 2.48	-2.6 ± 3.2	[-1.34, -0.34]	*0.003**	-0.93	4.0	-0.573	[-2.76, 1.62]	*0.597*
PPG	15	28.2 ± 2.73	27.7 ± 2.81	-2.1 ± 2.6	[-1.01, -0.04]	*0.037**	-0.6				
Cross-sectional area (mm$^{2)}$											
RF Distal											
HRG	16	794 ± 156.1	813.5 ± 169.24	2.8 ± 10.0	[-22.19, 61.16]	*0.335*	0.25	5.4	-1.555	[-8.15, 5.05]	*0.634*
PPG	15	746.7 ± 215.6	776.1 ± 225.25	4.3 ± 7.8	[1.54, 57.12]	*0.040**	0.58				
RF Middle											
HRG	16	1215.4 ± 182.5	1248.6 ± 172.28	3.0 ± 5.3	[-1.87, 68.27]	*0.062*	0.50	5.4	4.165	[0.52, 7.81]	*0.027**
PPG	15	1208.5 ± 170.2	1196.0 ± 169.20	-1.1 ± 4.5	[-50.22, 25.29]	*0.490*	-0.18				
RF Proximal											
HRG	15	1461.3 ± 153.29	1426.8 ± 159.79	-1.5 ± 6.6	[-98.53, 29.51]	*0.265*	-0.31	4.5	-2.035	[-6.25, 2.17]	*0.330*
PPG	15	1438.2 ± 201.91	1442.7 ± 189.80	0.5 ± 4.4	[-32.79, 41.91]	*0.797*	0.07				
Muscle thickness (mm)											
VL Distal											
HRG	16	24.2 ± 3.90	25.0 ± 3.50	3.8 ± 5.2	[0.26, 1.35]	*0.006**	0.79	4.4	2.249	[-1.34, 5.84]	*0.210*
PPG	15	22.2 ± 3.77	22.5 ± 4.03	1.5 ± 4.5	[-0.27, 0.84]	*0.292*	0.28				
VL Middle											
HRG	16	24.3 ± 4.81	25.2 ± 5.10	3.6 ± 3.5	[0.46,1.34]	*<.001**	1.09	4.2	3.149	[0.79, 5.51]	*0.011**
PPG	15	23.6 ± 3.39	23.6 ± 3.52	0.1 ± 3.4	[-0.31, 0.47]	*0.665*	0.11				
VL Proximal											
HRG	8	18.4 ± 9.54	19.2 ± 9.71	5.0 ± 11.5	[-0.60, 2.26]	*0.216*	0.48	9.0	-1.431	[-11.74, 8.88]	*0.766*
PPG	5	20.5 ± 3.95	20.7 ± 4.52	-1.0 ± 7.3	[-1.22, 1.54]	*0.764*	0.14				

Abbreviations: HRG: Heavy-load resistance group, PPG: Power-Plyo Group, CI: Confidence interval, LB: lower bound, UB: Upper bound, ES: Effect size (Cohens D), VL: Vastus Lateralis, RF: Rectus femoris, mm: millimetre, mm^2: squared millimetres

Table 6: Muscle architecture results

Change from baseline									Between group differences		
Variables and groups	n	Pre-test Mean ± SD	Post-test Mean ± SD	Δ% ± SD	95% CI (LB, UB)	*p*-value	ES	CV	Mean (%)	95% CI (LB, UB)	*p*-value
Pennation angle (degrees)											
HRG	16	14.5 ± 3.49	15.1 ± 3.16	6.2 ± 20.8	[-1.08, 2.28]	*0.461*	0.19				
PPG	15	12.3 ± 2.97	12.6 ± 2.16	5.0 ± 17.1	[-0.78, 1.34]	*0.579*	0.15	20.3	1.080	[-12.94, 15.10]	*0.876*
Fascicle length (mm)											
HRG	16	103.3 ± 16.03	104.5 ± 28.95	1.5 ± 22.0	[-11.78, 14.12]	*0.849*	0.05				
PPG	15	114.0 ± 24.23	109.4 ± 15.45	-1.6±16.3	[-15.04, 5.99]	*0.372*	-0.24	21.6	3.054	[-11.27, 17.38]	*0.666*

Abbreviations: HRG: Heavy-load resistance group, PPG: Power-Plyo Group, CI: Confidence interval, LB: lower bound, UB: Upper bound, ES: Effect size (Cohens D)

Bench-press showed a significant difference in between group change (6.64%; P = 0.030) and increased significantly only in HRG (HRG: 5.2% ± 5.6%; ES: 0.97; P = 0.002 and PPG: -1.5% ± 9.7%; ES: -0.15; P = 0.583). Squat increased significantly in both groups (HRG: 14.5% ± 10.8%; ES 1.79; P = < 0.001 and PPG: 6.0% ± 7.3%; ES: 0.87; P = 0.006), but significantly more in the HRG group (8.56%; P = 0.006). Keiser absolute showed no significant difference in percentage change between groups (5.03%; P = 0.133) and increased significantly only in HRG (HRG: 9.6% ± 9.5%; ES: 0.87; P = 0.003 and PPG: 4.6% ± 8.6%; ES: 0.49; P = 0.080). Keiser relative score also showed no significant difference in percentage change between groups (3.62%; P = 0.276) and increased significantly only in HRG (HRG: 8.5% ± 9.8%; ES: 0.85; P = 0.004 and PPG: 4.9% ± 8.2%; ES: 0.52; P = 0.065). MVC increased significantly in both groups (HRG: 5.4% ± 6.3%; ES: 0.87; P = 0.005 and PPG: 4.4% ± 6.5%; ES: 0.71; P = 0.016) with no difference in percentage change between groups (1.00%; P = 0.133).

Table 7: Strength results

Change from baseline								Between group differences		
Variables and groups	n	Pre-test Mean ± SD	Post-test Mean ± SD	Δ% ± SD	95% CI (LB, UB)	*p*-value	ES	Mean (%)	95% CI (LB, UB)	*p*-value
Benchpress (kg)										
HRG	15	53.2 ± 6.91	55.8 ± 7.18	5.2 ± 5.6	[1.14, 4.19]	0.002*	0.97	6.64	[0.68, 12.59]	0.030*
PPG	14	48.8 ± 5.61	48.0 ± 7.01	-1.5 ± 9.7	[-3.45, 2.03]	0.583	-0.15			
Squat (kg)										
HRG	14	83.0 ± 13.5	94.1 ± 11.71	14.5 ± 10.8	[7.503, 14.64]	< .001*	1.79	8.56	[2.74, 13.29]	
PPG	14	47.27 ± 4.1	48.07 ± 4.44	6.0 ± 7.3	[0.16, 1.44]	0.006*	0.87			0.006*
Keiser absolute (newton)										
HRG	16	1826 ± 348	1990 ± 325	9.6 ± 9.5	[63.63, 264.5]	0.003*	0.87	5.03	[-1.63, 11.68]	0.133
PPG	15	1729 ± 278	1804 ± 293	4.6 ± 8.6	[-10.13, 159.73]	0.080	0.49			
Keiser relative (newton/BW)										
HRG	16	26.3 ± 3.29	28.5 ± 4.35	8.5 ± 9.8	[0.81, 3.57]	0.004*	0.85	3.62	[-3.04, 10.28]	0.276
PPG	15	26.5 ± 4.39	27.7 ± 4.91	4.9 ± 8.2	[-0.09, 2.57]	0.065	0.52			
MVC (newton)										
HRG	15	531.5 ± 76.8	559.6 ± 85.6	5.4 ± 6.3	[10.12, 46.06]	0.005*	0.87	1.00	[-3.78, 5.79]	0.671
PPG	15	454.0 ± 78	474.7 ± 90.2	4.4 ± 6.5	[4.50, 36.74]	0.016*	0.71			

Abbreviations: HRG: Heavy-load resistance group, PPG: Power-Plyo Group, CI: Confidence interval, LB: lower bound, UB: Upper bound, ES: Effect size (Cohens D), MVC: Maximum voluntary contraction

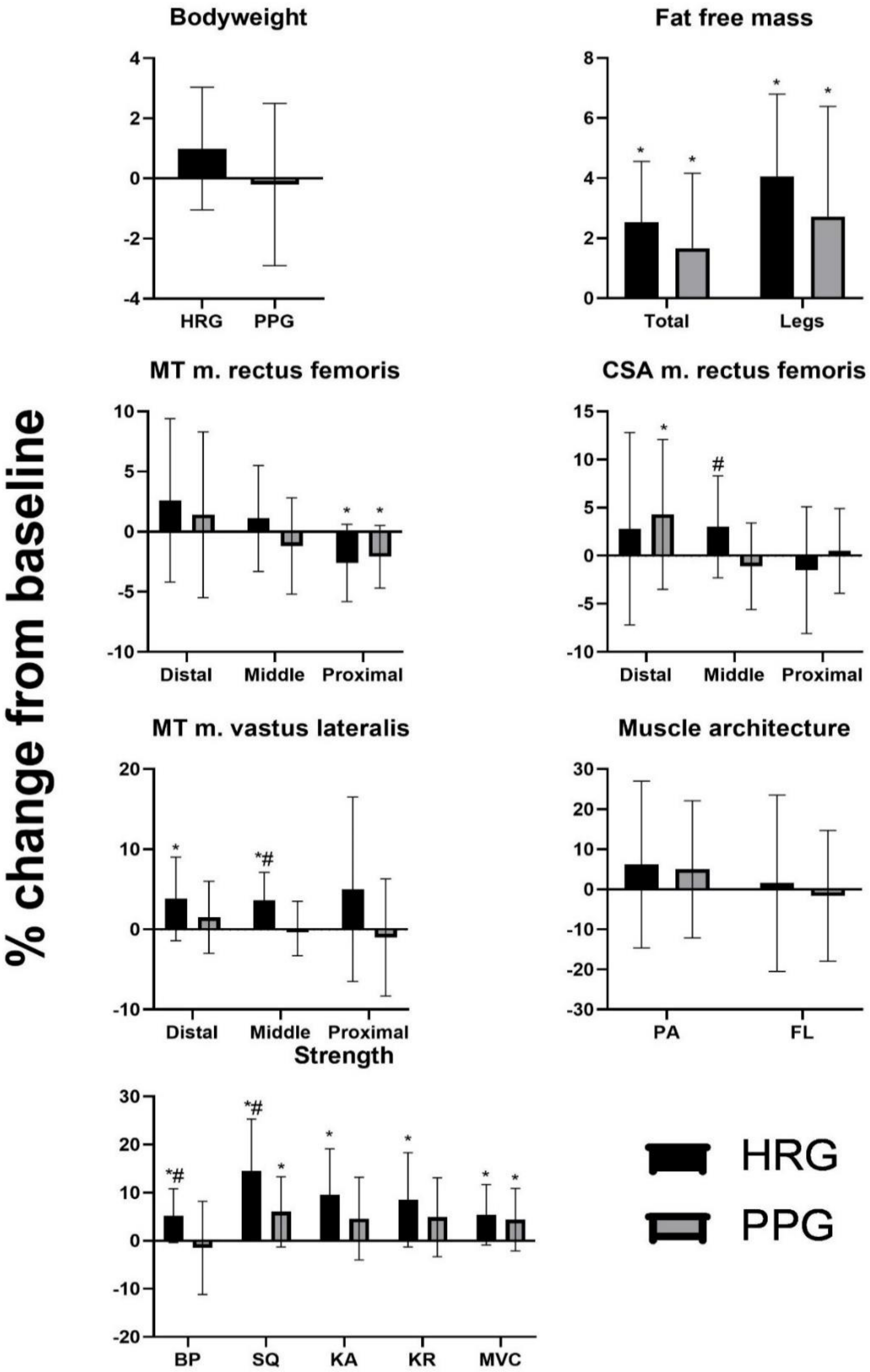


Figure 1: Mean % change from baseline.

 # Significant difference between group change

** Significant change from baseline*

Abbreviations: HRG: Heavy-load resistance group, PPG: Power-Plyo Group, MT: Muscle thickness, CSA: Cross-sectional area, BP: Benchpress, SQ: Squat, KA: Keiser absolute, KR: Keiser relative, MVC: Maximum voluntary contraction

Discussion

The main findings of the study indicate that both heavy load resistance training and power/plyometric training resulted in increases in fat-free mass. However, hypertrophy of the vastus lateralis and rectus femoris muscles showed regional and non-homogeneous patterns with greater effect in the middle thigh region from heavy load resistance training. Heavy load resistance training led to greater improvements in squat and bench press performance, with no significant differences observed in Fmax and MVC.

Heavy load resistance-, power- and plyometric training are all effective methods for enhancing vital physical characteristics of both male and female handball players, such as sprinting, jumping, throwing and change of direction characterized by the ability to rapidly produce force (RFD). [4,8,13,17,23–28] They do so by developing muscular strength by stimulating both force and velocity abilities. [1,11] Each training modality requires substantial muscle activation generating different amount force and velocity across the force-velocity continuum. [29] This leads to specific muscular demands that influence subsequent morphological and neural adaptions.

Increasing muscle size has been viewed as essential for handball players to increase force production and has traditionally been viewed as mainly achieved through heavy load resistance training. [7,10,11,30] Recent summaries of the available literature challenged this view, finding significant hypertrophy from plyometric training across ages, sexes and training experience. [8,10] This is supported by findings in the present study showing significant increases with no group difference (0.84%; $P = 0.309$) in FFM indicating hypertrophy in both groups (HRG: 2.53% ± 2.03%; ES: 1.24; $P = < .001$ vs PPG; 1.67% ± 2.49%; ES: 0.69; $P = 0.018$). The primary driver for hypertrophy, via muscle protein synthesis, is thought to be sufficient mechanical tension recruiting high threshold motor units, including type II muscle fibers, as well as muscle disruption and metabolic stress. [10,31,32] The limited time under mechanical tension and lack of metabolic stress has previously led to the assumption that power and plyometric training provide to little stimulus for hypertrophy to occur, but the present findings raises questions regarding these generally accepted mechanisms of hypertrophy . [1,8,10] Hypertrophy seen from power and plyometric training may indicate that brief exposure to high force mechanical tension is sufficient to elicit hypertrophy. [10] This may stem from the stimuli applied fast twitch muscle fibers known to be more sensitive to hypertrophy compared to slow twitch fibers. [10,33,34] While heavy load training usually recruits motor units based on the size principle (small to large), explosive training may need less time under tension due to recruiting larger high threshold motor units dominated by fast twitch fibers. [6,10,35,36] Another factor to consider is the challenge of matching workload between maximal and explosive strength training, whereas 1:1 ratio of sets x repetitions cannot be assumed to achieve the same stimuli. [10,37] This present study used a higher number of repetitions and sets in PPG based on previously shown effective volume this may account for time under mechanical tension. Using higher total volume (sets x reps) may therefore be a valid method to induce hypertrophy through accumulating time under high force mechanical tension. The lack of metabolic stress induced by this type of training may also facilitate easier implementation during in-season for handball players. [1]

While total hypertrophy showed no significant difference between groups, in line with the findings of Grgic et al (2021), regional and non-homogenous patterns of changes in muscle size has previously been shown in the literature between training modalities. [13,38] This pattern was observed when comparing changes between groups in measures of muscle thickness and cross-sectional area indicating better effect of heavy load training in the middle region of both rectus femoris (CSA; 4.165%; P = 0.027) and vastus lateralis (MT; 3.149%; P =0.01) compared to PPG. When assessing change from baseline, significant increases in distal RF-CSA were found in PPG (4.3% ± 7.8%; ES: 0.58; P = 0.04) and increases in distal and middle VL-MT were found in HRG (Distal; 3.8% ± 5.2%; ES: 0.79; P = 0.006 and Middle; 3.6% ± 3.5%; ES: 1.09; P = <.001). This non-homogenous pattern in hypertrophy is thought to be the consequence of different muscle groups as well as specific regions of individual muscles fulfilling distinct functional roles with regards to producing force at different velocities or movements. [13] This induces selective muscle recruitment and subsequent mechanical tension may explain the observed patterns in hypertrophy.

Earp et al, (2015), performed a similar study comparing the effects of heavy squats vs jump squats also finding similar non-homogeneous patterns between groups. They hypothesized that certain regions of the muscles may be suited for high force production while other may be better at inducing high velocities. Muscle mass closer to the joint’s axis of rotation is beneficial for high velocity movements due to reduced moment of inertia, while high force production at low velocity is more dependent on CSA favouring muscle mass at the middle site .[13,39,40] The HRG effect on muscle mass in the middle region should therefore allow the production of more force, but it may compromise the ability to achieve high velocity through increased moment of inertia. [13,39] While the hypothesized greater effect of HRG at the middle site was observed, no group difference were found in the distal site. PPG did show significant change from baseline in distal RF-CSA, but so did HRG in distal VL-MT. This indicates that heavy load is equally effective at inducing hypertrophy distally compared to PPG. It is important to note that distal muscle mass in the thigh, closer to the knee joint, may primarily provide specific benefits for achieving high velocity in knee dominant closed-chain movements such as squatting or jumping. [13] During sprinting the hip joint is more important, and distal hypertrophy could therefore require greater force production from the hip extensors and flexors to accelerate the thigh around the hip. [13] These distal adaptations observed may therefore be specifically relevant for jumping but may not directly translate to other movements like sprinting.

Maximal strength refers to production of high force at low velocities, and is subsequently primary driven by muscle size. [11] Maximal strength can improve force production across the force-velocity spectrum and has shown strong association with RFD. [31] Heavy load resistance training is viewed as the most effective for increasing maximal strength, due to its specificity and effect on CSA, while explosive training has shown effects on maximal muscle strength it is viewed as more effective at improving specific neuromuscular aspects of high velocity movements. [1,11] The present study supports heavy load resistance training as a effective method, with significant increases in all strength parameters. Both 1RM squat (8.56%; $P = 0.006$) and benchpress (6.64%; $P = 0.030$) increased significantly more in HRG, while no significant difference were found in Fmax and MVC. This overall greater effect in maximal strength is not surprising due to the specific neural and morphological adaptions to heavy load resistance training. While HRG showed greater effect, it should be noted that PPG achieved maintenance or improvement in all strength measures, including significant increase in squat (6.0% ± 7.3%; ES: 0.87; $P = 0.006$). This is likely due to the increases in muscle size displayed in both groups, but specific neural and morphological adaptions in HRG leads to a greater expression of maximal force. Overall this should highlight the effectiveness of heavy load resistance training for athletes looking to increase their maximal force production, but during in-season power- and plyometric training may be sufficient to maintain maximal strength.

In conclusion both training modalities show effectiveness in increasing total FFM, with regional and non-homogenous hypertrophy patterns in vastus lateralis and rectus femoris, possible due to movement specific demands eliciting specific force and velocity beneficial adaptions. Maximal strength is more effectively increased via heavy load training, but power- and plyometric training seem to able to maintain it during in-season in female handball players.

Perspective

This study highlights the need for further investigation in the area of strength training during the in-season period, particularly focusing on the effectiveness of commonly used training methods. It is important to explore the specific effects of these methods on female athletes and to extend the research to elite-level athletes. While this study examines two training modalities in isolation, there is a need to further investigate the potential enhanced effects of combined training. The findings also reveal interesting insights into the mechanisms of hypertrophy, particularly regarding the effects of plyometrics, which warrant further exploration. Additionally, it is essential to investigate whether the observed regional and non-homogenous hypertrophy patterns have distinct performance benefits. Overall, more research is needed to fully understand the implications and optimize the use of different training modalities in the context of in-season strength training.

References

1. Cormier P, Freitas TT, Seaman K. A systematic review of resistance training methodologies for the development of lower body concentric mean power, peak power, and mean propulsive power in team-sport athletes. *Sports Biomech*. Published online August 4, 2021:1-34. doi:10.1080/14763141.2021.1948601
2. Suchomel TJ, Nimphius S, Stone MH. The Importance of Muscular Strength in Athletic Performance. *Sports Med*. 2016;46(10):1419-1449. doi:10.1007/s40279-016-0486-0
3. Michalsik L, Aagaard P. Physical demands in elite team handball: Comparisons between male and female players. *J Sports Med Phys Fitness*. 2014;55.
4. Chelly MS, Ghenem MA, Abid K, Hermassi S, Tabka Z, Shephard RJ. Effects of in-Season Short-Term Plyometric Training Program on Leg Power, Jump- and Sprint Performance of Soccer Players. *J Strength Cond Res*. 2010;24(10). https://journals.lww.com/nsca-jscr/Fulltext/2010/10000/Effects_of_in_Season_Short_Term_Plyometric.13.aspx

5. Blazevich AJ, Gill ND, Zhou S. Intra- and intermuscular variation in human quadriceps femoris architecture assessed in vivo. *J Anat*. 2006;209(3):289-310. doi:https://doi.org/10.1111/j.1469-7580.2006.00619.x
6. Suchomel TJ, Nimphius S, Bellon CR, Stone MH. The Importance of Muscular Strength: Training Considerations. *Sports Med*. 2018;48(4):765-785. doi:10.1007/s40279-018-0862-z
7. Wagner H, Gierlinger M, Adzamija N, Ajayi S, Bacharach DW, von Duvillard SP. Specific Physical Training in Elite Male Team Handball. *J Strength Cond Res*. 2017;31(11):3083-3093. doi:10.1519/JSC.0000000000002094
8. Arntz F, Mkaouer B, Markov A, et al. Effect of Plyometric Jump Training on Skeletal Muscle Hypertrophy in Healthy Individuals: A Systematic Review With Multilevel Meta-Analysis. *Front Physiol*. 2022;13. doi:10.3389/fphys.2022.888464
9. Ramirez-Campillo R, García-Pinillos F, T. Nikolaidis P, Clemente F, Gentil P, García-Hermoso A. Body composition adaptations to lower-body plyometric training: a systematic review and meta-analysis. *Biol Sport*. 2022;39(2):273-287. doi:10.5114/biolsport.2022.104916
10. Grgic J, Schoenfeld BJ, Mikulic P. Effects of plyometric vs. resistance training on skeletal muscle hypertrophy: A review. *J Sport Health Sci*. 2021;10(5):530-536. doi:https://doi.org/10.1016/j.jshs.2020.06.010
11. Cormie P, McGuigan MR, Newton RU. Developing Maximal Neuromuscular Power. *Sports Med*. 2011;41(1):17-38. doi:10.2165/11537690-000000000-00000
12. Slimani M, Chamari K, Miarka B, Del Vecchio FB, Chéour F. Effects of Plyometric Training on Physical Fitness in Team Sport Athletes: A Systematic Review. *J Hum Kinet*. 2016;53:231-247. doi:10.1515/hukin-2016-0026
13. EARP JE, NEWTON RU, CORMIE P, BLAZEVICH AJ. Inhomogeneous Quadriceps Femoris Hypertrophy in Response to Strength and Power Training. *Med Sci Sports Exerc*. 2015;47(11). https://journals.lww.com/acsm-msse/Fulltext/2015/11000/Inhomogeneous_Quadriceps_Femoris_Hypertrophy_in.18.aspx
14. Haun CT, Vann CG, Roberts BM, Vigotsky AD, Schoenfeld BJ, Roberts MD. A Critical Evaluation of the Biological Construct Skeletal Muscle Hypertrophy: Size Matters but So Does the Measurement. *Front Physiol*. 2019;10. Accessed April 13, 2023. https://www.frontiersin.org/articles/10.3389/fphys.2019.00247

15. Franchi MV, Raiteri BJ, Longo S, Sinha S, Narici MV, Csapo R. Muscle Architecture Assessment: Strengths, Shortcomings and New Frontiers of in Vivo Imaging Techniques. *Ultrasound Med Biol*. 2018;44(12):2492-2504. doi:10.1016/j.ultrasmedbio.2018.07.010

16. Blazevich AJ, Gill ND, Bronks R, Newton RU. Training-Specific Muscle Architecture Adaptation after 5-wk Training in Athletes. *Med Sci Sports Exerc*. 2003;35(12):2013. doi:10.1249/01.MSS.0000099092.83611.20

17. Sammoud S, Bouguezzi R, Ramirez-Campillo R, et al. Effects of plyometric jump training versus power training using free weights on measures of physical fitness in youth male soccer players. *J Sports Sci*. 2022;40(2):130-137. doi:10.1080/02640414.2021.1976570

18. Sánchez M, Sanchez-Sanchez J, Nakamura FY, Clemente FM, Romero-Moraleda B, Ramirez-Campillo R. Effects of Plyometric Jump Training in Female Soccer Player’s Physical Fitness: A Systematic Review with Meta-Analysis. *Int J Environ Res Public Health*. 2020;17(23). doi:10.3390/ijerph17238911

19. Lixandrão ME, Ugrinowitsch C, Bottaro M, et al. Vastus Lateralis Muscle Cross-sectional Area Ultrasonography Validity for Image Fitting in Humans. *J Strength Cond Res*. 2014;28(11):3293. doi:10.1519/JSC.0000000000000532

20. Sarto F, Spörri J, Fitze DP, Quinlan JI, Narici MV, Franchi MV. Implementing Ultrasound Imaging for the Assessment of Muscle and Tendon Properties in Elite Sports: Practical Aspects, Methodological Considerations and Future Directions. *Sports Med*. 2021;51(6):1151-1170. doi:10.1007/s40279-021-01436-7

21. Redden J, Stokes K, Williams S. Establishing the Reliability and Limits of Meaningful Change of Lower Limb Strength and Power Measures during Seated Leg Press in Elite Soccer Players. *J Sports Sci Med*. 2018;17(4):539-546.

22. Izquierdo M, González-Badillo JJ, Häkkinen K, et al. Effect of Loading on Unintentional Lifting Velocity Declines During Single Sets of Repetitions to Failure During Upper and Lower Extremity Muscle Actions. *Int J Sports Med*. 2006;27(9):718-724. doi:10.1055/s-2005-872825

23. Spieszny M, Zubik M. Modification of Strength Training Programs in Handball Players and its Influence on Power During the Competitive Period. *J Hum Kinet*. 2018;63:149-160. doi:10.2478/hukin-2018-0015

24. Hermassi S, van den Tillaar R, Khlifa R, Chelly MS, Chamari K. Comparison of In-Season-Specific Resistance vs. A Regular Throwing Training Program on Throwing

Velocity, Anthropometry, and Power Performance in Elite Handball Players. *J Strength Cond Res*. 2015;29(8). https://journals.lww.com/nsca-jscr/Fulltext/2015/08000/Comparison_of_In_Season_Specific_Resistance_vs__A.5.aspx

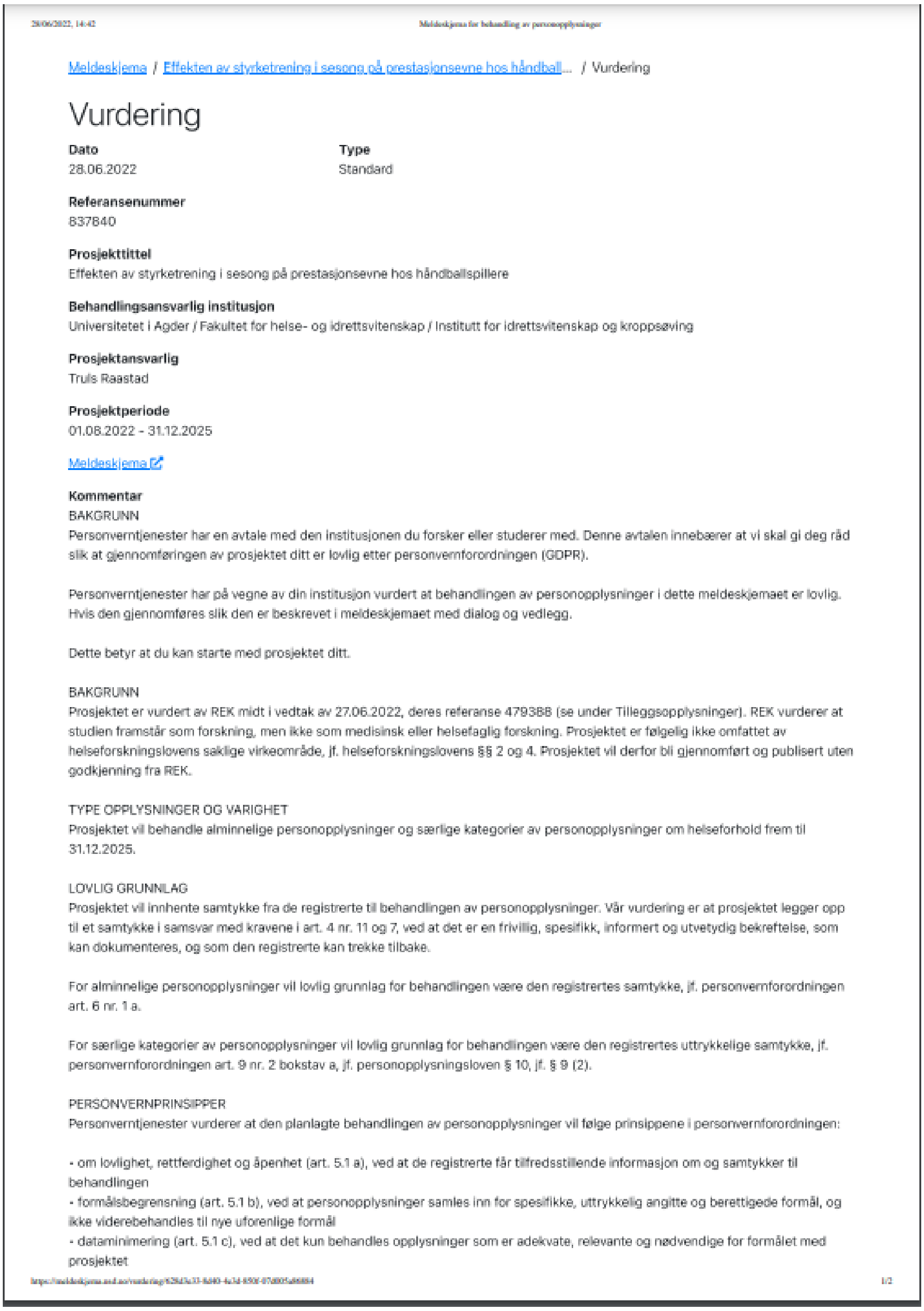
25. Falch HN, Haugen ME, Kristiansen EL, van den Tillaar R. Effect of Strength vs. Plyometric Training upon Change of Direction Performance in Young Female Handball Players. *Int J Environ Res Public Health*. 2022;19(11):6946. doi:10.3390/ijerph19116946
26. Hammami M, Gaamouri N, Shephard RJ, Chelly MS. Effects of Contrast Strength vs. Plyometric Training on Lower-Limb Explosive Performance, Ability to Change Direction and Neuromuscular Adaptation in Soccer Players. *J Strength Cond Res*. 2019;33(8):2094-2103. doi:10.1519/JSC.0000000000002425
27. Chaabene H, Negra Y, Moran J, et al. Plyometric Training Improves Not Only Measures of Linear Speed, Power, and Change-of-Direction Speed But Also Repeated Sprint Ability in Young Female Handball Players. *J Strength Cond Res*. 2021;35(8). https://journals.lww.com/nsca-jscr/Fulltext/2021/08000/Plyometric_Training_Improves_Not_Only_Measures_of.22.aspx
28. Loturco I, Pereira LA, Reis VP, et al. Power training in elite young soccer players: Effects of using loads above or below the optimum power zone. *J Sports Sci*. 2020;38(11-12):1416-1422. doi:10.1080/02640414.2019.1651614
29. Taber C, Bellon C, Abbott H, Bingham GE. Roles of Maximal Strength and Rate of Force Development in Maximizing Muscular Power. *Strength Cond J*. 2016;38(1):71. doi:10.1519/SSC.0000000000000193
30. Manchado C, Tortosa-Martínez J, Vila H, Ferragut C, Platen P. Performance Factors in Women's Team Handball: Physical and Physiological Aspects—A Review. *J Strength Cond Res*. 2013;27(6):1708. doi:10.1519/JSC.0b013e3182891535
31. Travis SK, Ishida A, Taber CB, Fry AC, Stone MH. Emphasizing Task-Specific Hypertrophy to Enhance Sequential Strength and Power Performance. *J Funct Morphol Kinesiol*. 2020;5(4):76-0. doi:10.3390/jfmk5040076
32. Schoenfeld BJ. The Mechanisms of Muscle Hypertrophy and Their Application to Resistance Training. *J Strength Cond Res*. 2010;24(10):2857. doi:10.1519/JSC.0b013e3181e840f3

33. Plotkin DL, Roberts MD, Haun CT, Schoenfeld BJ. Muscle Fiber Type Transitions with Exercise Training: Shifting Perspectives. *Sports*. 2021;9(9). doi:10.3390/sports9090127
34. Medler S. Mixing it up: the biological significance of hybrid skeletal muscle fibers. *J Exp Biol*. 2019;222:jeb200832. doi:10.1242/jeb.200832
35. Henneman E, Clamann HP, Gillies JD, Skinner RD. Rank order of motoneurons within a pool: law of combination. *J Neurophysiol*. 1974;37(6):1338-1349. doi:10.1152/jn.1974.37.6.1338
36. Macaluso F, Isaacs AW, Myburgh KH. Preferential Type II Muscle Fiber Damage From Plyometric Exercise. *J Athl Train*. 2012;47(4):414-420. doi:10.4085/1062-6050-47.4.13
37. Mohamad NI, Cronin JB, Nosaka KK. Difference in Kinematics and Kinetics Between High- and Low-Velocity Resistance Loading Equated by Volume: Implications for Hypertrophy Training. *J Strength Cond Res*. 2012;26(1). https://journals.lww.com/nsca-jscr/Fulltext/2012/01000/Difference_in_Kinematics_and_Kinetics_Between.36.aspx
38. Zabaleta-Korta A, Fernández-Peña E, Torres-Unda J, Francés M, Zubillaga A, Santos-Concejero J. *Regional Hypertrophy: The Role of Exercise Resistance Profile in Trained Women*.; 2022. doi:10.21203/rs.3.rs-1530884/v1
39. Abe T, Kumagai K, Brechue WF. Fascicle length of leg muscles is greater in sprinters than distance runners. *Med Sci Sports Exerc*. 2000;32(6):1125-1129. doi:10.1097/00005768-200006000-00014
40. Myers MJ, Steudel K. Effect of Limb Mass and its Distribution on the Energetic Cost of Running. *J Exp Biol*. 1985;116(1):363-373. doi:10.1242/jeb.116.1.363

Part 3

Appendices

Appendix 1 - Approval by the Norwegian Centre for Research Data



28/06/2022, 14:42 Meldeskjema for behandling av personopplysninger

Meldeskjema / Effekten av styrketrening i sesong på prestasjonsevne hos håndball... / Vurdering

Vurdering

Dato
28.06.2022

Type
Standard

Referansenummer
837840

Prosjekttittel
Effekten av styrketrening i sesong på prestasjonsevne hos håndballspillere

Behandlingsansvarlig institusjon
Universitetet i Agder / Fakultet for helse- og idrettsvitenskap / Institutt for idrettsvitenskap og kroppsøving

Prosjektansvarlig
Truls Raastad

Prosjektperiode
01.08.2022 - 31.12.2025

Meldeskjema

Kommentar

BAKGRUNN
Personverntjenester har en avtale med den institusjonen du forsker eller studerer med. Denne avtalen innebærer at vi skal gi deg råd slik at gjennomføringen av prosjektet ditt er lovlig etter personvernforordningen (GDPR).

Personverntjenester har på vegne av din institusjon vurdert at behandlingen av personopplysninger i dette meldeskjemaet er lovlig. Hvis den gjennomføres slik den er beskrevet i meldeskjemaet med dialog og vedlegg.

Dette betyr at du kan starte med prosjektet ditt.

BAKGRUNN
Prosjektet er vurdert av REK midt i vedtak av 27.06.2022, deres referanse 479388 (se under Tilleggsopplysninger). REK vurderer at studien framstår som forskning, men ikke som medisinsk eller helsefaglig forskning. Prosjektet er følgelig ikke omfattet av helseforskningslovens saklige virkeområde, jf. helseforskningslovens §§ 2 og 4. Prosjektet vil derfor bli gjennomført og publisert uten godkjenning fra REK.

TYPE OPPLYSNINGER OG VARIGHET
Prosjektet vil behandle alminnelige personopplysninger og særlige kategorier av personopplysninger om helseforhold frem til 31.12.2025.

LOVLIG GRUNNLAG
Prosjektet vil innhente samtykke fra de registrerte til behandlingen av personopplysninger. Vår vurdering er at prosjektet legger opp til et samtykke i samsvar med kravene i art. 4 nr. 11 og 7, ved at det er en frivillig, spesifikk, informert og utvetydig bekreftelse, som kan dokumenteres, og som den registrerte kan trekke tilbake.

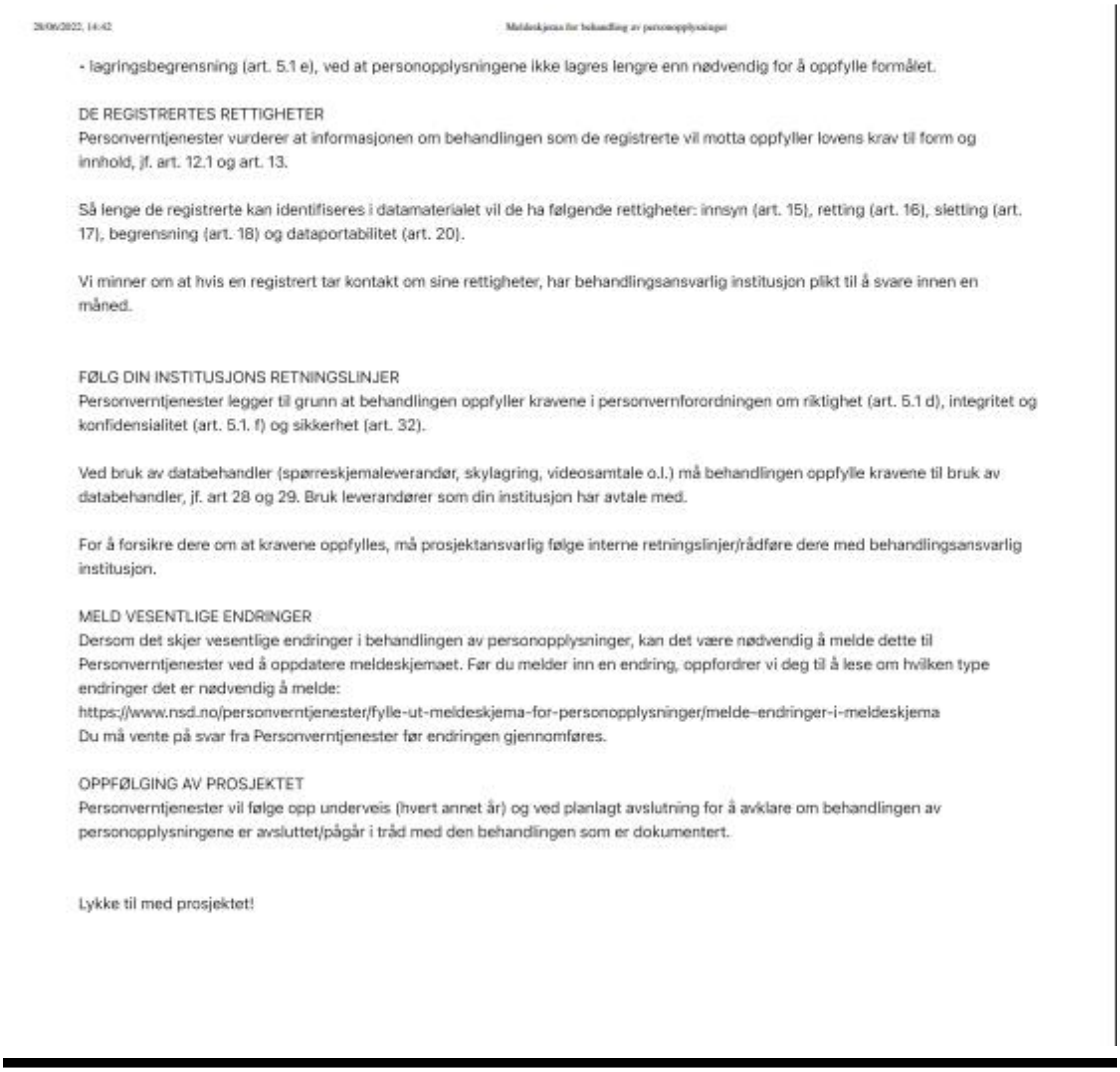
For alminnelige personopplysninger vil lovlig grunnlag for behandlingen være den registrertes samtykke, jf. personvernforordningen art. 6 nr. 1 a.

For særlige kategorier av personopplysninger vil lovlig grunnlag for behandlingen være den registrertes uttrykkelige samtykke, jf. personvernforordningen art. 9 nr. 2 bokstav a, jf. personopplysningsloven § 10, jf. § 9 (2).

PERSONVERNPRINSIPPER
Personverntjenester vurderer at den planlagte behandlingen av personopplysninger vil følge prinsippene i personvernforordningen:

- om lovlighet, rettferdighet og åpenhet (art. 5.1 a), ved at de registrerte får tilfredsstillende informasjon om og samtykker til behandlingen
- formålsbegrensning (art. 5.1 b), ved at personopplysninger samles inn for spesifikke, uttrykkelig angitte og berettigede formål, og ikke viderebehandles til nye uforenlige formål
- dataminimering (art. 5.1 c), ved at det kun behandles opplysninger som er adekvate, relevante og nødvendige for formålet med prosjektet

1/2



- lagringsbegrensning (art. 5.1 e), ved at personopplysningene ikke lagres lengre enn nødvendig for å oppfylle formålet.

DE REGISTRERTES RETTIGHETER
Personverntjenester vurderer at informasjonen om behandlingen som de registrerte vil motta oppfyller lovens krav til form og innhold, jf. art. 12.1 og art. 13.

Så lenge de registrerte kan identifiseres i datamaterialet vil de ha følgende rettigheter: innsyn (art. 15), retting (art. 16), sletting (art. 17), begrensning (art. 18) og dataportabilitet (art. 20).

Vi minner om at hvis en registrert tar kontakt om sine rettigheter, har behandlingsansvarlig institusjon plikt til å svare innen en måned.

FØLG DIN INSTITUSJONS RETNINGSLINJER
Personverntjenester legger til grunn at behandlingen oppfyller kravene i personvernforordningen om riktighet (art. 5.1 d), integritet og konfidensialitet (art. 5.1. f) og sikkerhet (art. 32).

Ved bruk av databehandler (spørreskjemaleverandør, skylagring, videosamtale o.l.) må behandlingen oppfylle kravene til bruk av databehandler, jf. art 28 og 29. Bruk leverandører som din institusjon har avtale med.

For å forsikre dere om at kravene oppfylles, må prosjektansvarlig følge interne retningslinjer/rådføre dere med behandlingsansvarlig institusjon.

MELD VESENTLIGE ENDRINGER
Dersom det skjer vesentlige endringer i behandlingen av personopplysninger, kan det være nødvendig å melde dette til Personverntjenester ved å oppdatere meldeskjemaet. Før du melder inn en endring, oppfordrer vi deg til å lese om hvilken type endringer det er nødvendig å melde:
https://www.nsd.no/personverntjenester/fylle-ut-meldeskjema-for-personopplysninger/melde-endringer-i-meldeskjema
Du må vente på svar fra Personverntjenester før endringen gjennomføres.

OPPFØLGING AV PROSJEKTET
Personverntjenester vil følge opp underveis (hvert annet år) og ved planlagt avslutning for å avklare om behandlingen av personopplysningene er avsluttet/pågår i tråd med den behandlingen som er dokumentert.

Lykke til med prosjektet!

Appendix 2 Application for ethical approval of research project

Thomas Bjørnsen

Besøksadresse:
Universitetsveien 25
Kristiansand

Ref: [object Object]

Tidspunkt for godkjenning: : 18/08/2022

Søknad om etisk godkjenning av forskningsprosjekt - Effekten av styrketrening i sesong på prestasjonsevne hos håndballspillere

Vi informerer om at din søknad er ferdig behandlet og godkjent.

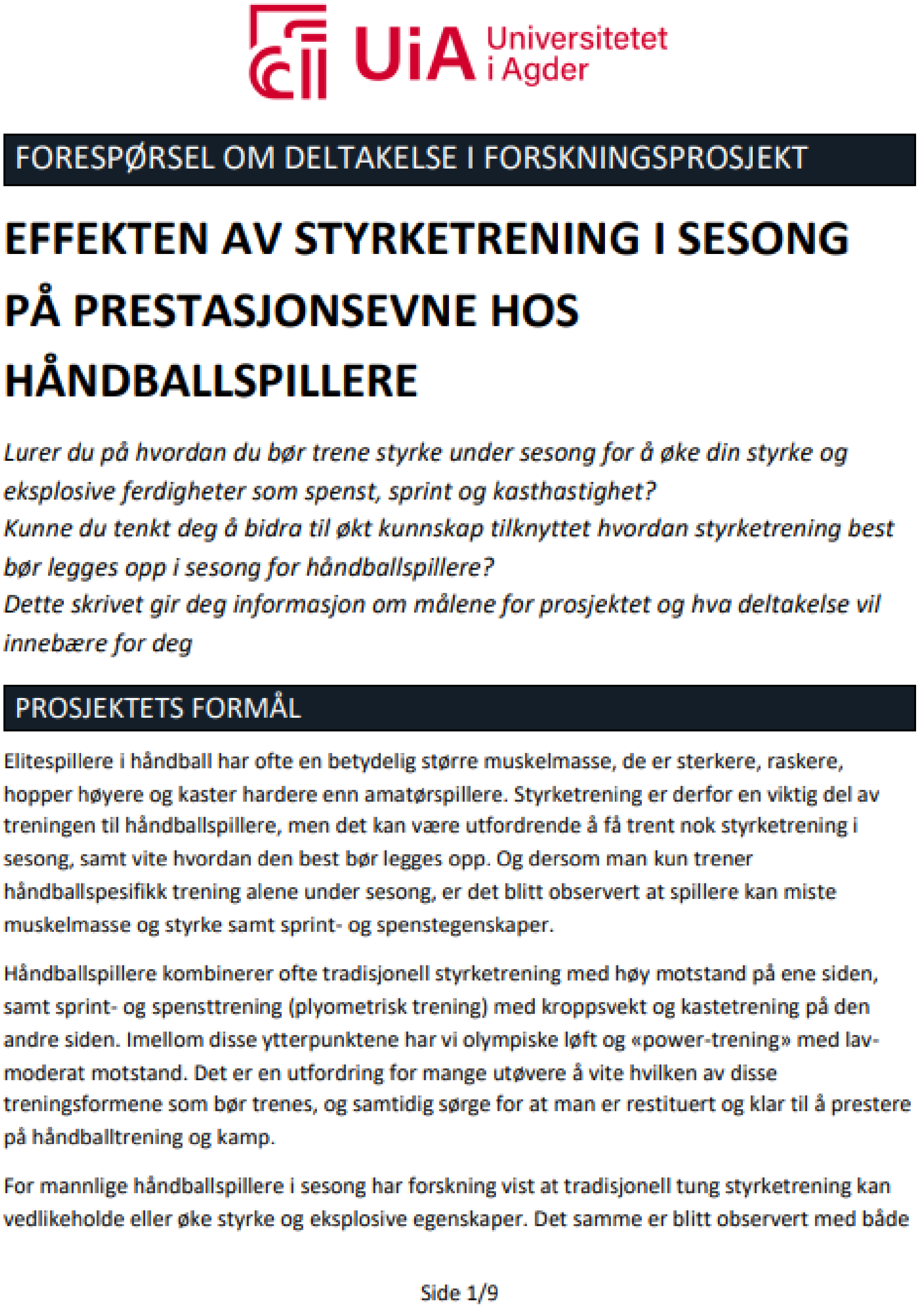
Kommentar fra godkjenner:

Hilsen
Forskningsetisk komite
Fakultet for helse - og idrettsvitenskap
Universitetet i Agder

UNIVERSITETET I AGDER
POSTBOKS 422 4604 KRISTIANSAND
TELEFON 38 14 10 00
ORG. NR 970 546 200 MVA - post@uia.no -
www.uia.no

FAKTURAADRESSE:
UNIVERSITETET I AGDER,
FAKTURAMOTTAK
POSTBOKS 383 ALNABRU 0614 OSLO

APPENDIX 3 Informed written consent signed by the subjects



UiA Universitetet i Agder

FORESPØRSEL OM DELTAKELSE I FORSKNINGSPROSJEKT

EFFEKTEN AV STYRKETRENING I SESONG PÅ PRESTASJONSEVNE HOS HÅNDBALLSPILLERE

Lurer du på hvordan du bør trene styrke under sesong for å øke din styrke og eksplosive ferdigheter som spenst, sprint og kasthastighet?
Kunne du tenkt deg å bidra til økt kunnskap tilknyttet hvordan styrketrening best bør legges opp i sesong for håndballspillere?
Dette skrivet gir deg informasjon om målene for prosjektet og hva deltakelse vil innebære for deg

PROSJEKTETS FORMÅL

Elitespillere i håndball har ofte en betydelig større muskelmasse, de er sterkere, raskere, hopper høyere og kaster hardere enn amatørspillere. Styrketrening er derfor en viktig del av treningen til håndballspillere, men det kan være utfordrende å få trent nok styrketrening i sesong, samt vite hvordan den best bør legges opp. Og dersom man kun trener håndballspesifikk trening alene under sesong, er det blitt observert at spillere kan miste muskelmasse og styrke samt sprint- og spenstegenskaper.

Håndballspillere kombinerer ofte tradisjonell styrketrening med høy motstand på ene siden, samt sprint- og spensttrening (plyometrisk trening) med kroppsvekt og kastetrening på den andre siden. Imellom disse ytterpunktene har vi olympiske løft og «power-trening» med lav-moderat motstand. Det er en utfordring for mange utøvere å vite hvilken av disse treningsformene som bør trenes, og samtidig sørge for at man er restituert og klar til å prestere på håndballtrening og kamp.

For mannlige håndballspillere i sesong har forskning vist at tradisjonell tung styrketrening kan vedlikeholde eller øke styrke og eksplosive egenskaper. Det samme er blitt observert med både sprint- og spenst-trening, samt power-trening. Men det mangler både forskning som direkte sammenligner effekten av de ulike treningsformene på håndballspillere i sesong, og generelt hvordan kvinnelige håndballspillere i sesong blir påvirket av styrketrening.

Av den grunn er det av interesse å sammenligne tilpasninger i muskelmasse, styrke, spenst og hurtighet mellom disse treningsformene under en treningsperiode i sesong. Resultatene kan hjelpe deg og andre håndballspillere til å sette opp hvilken styrketreningsform som bør prioriteres i sesong for utøvere med ulike utgangspunkt og egenskaper. I tillegg vil vi undersøke om treningsøktene gir ulike akutte treningsstimuli og restitusjonsforløp som kan forklare tilpasningene. Mer kunnskap om det kan hjelpe i å planlegge styrketreningen opp imot håndballkamper og trening. Dette er et tema som landslagstrener Thorir Hergeirsson har kommet med spesielt ønske om å undersøke nærmere for å forbedre prestasjonsutvikling i sesong for håndballspillere.

For å utforske dette inviterer vi nettopp deg til å delta. Du må være aktiv håndballspiller mellom 16 og 35 år (foreldresamtykke dersom under 18 år) og ha erfaring med styrketrening. Du kan ikke delta om du har skader i muskelskjelettapparatet som hindrer deg i å trene og yte maksimalt i styrke-spenst- og sprint-tester. Du kan heller ikke delta dersom du som kvinnelig utøver er gravid.

Prosjektet blir gjennomført av forskere tilknyttet Universitetet i Agder, Norges idrettshøgskole og Olympiatoppen, i samarbeid med Thorir Hergeirsson og landslagets fysiske trener Benjamin Jensen.

HVA INNEBÆRER DET FOR DEG Å DELTA I PROSJEKTET?

Deltakelse innebærer at hver utøver gjennomfører fysiske tester ved Universitetet i Agder. Deretter blir man randomisert (tilfeldig fordelt) i to treningsgrupper som skal trene i 16 uker under kampsesong. Tidspunkt for testing og trening er planlagt for høsten 2022 og 2023. I tillegg vil vi kartlegge treningsbelastning fra perioder med håndballtrening og kamper med sporingsenheter.

For å kunne delta er det ønskelig at hver deltaker:

- Gjennomfører fysiske tester fordelt på totalt syv dager
    - Én tilvenningsøkt og tester før og etter treningsperioden (opptil 2 timer per økt)
    - 4 «akutte» testdager i slutten av prosjektet (opptil 1 time per økt)
    - Testene må gjennomføres i utvilt tilstand før og etter treningsperioden samt på akutt testdag 1. Uthvilt tilstand betyr uten å ha gjennomført hard anstrengende trening de siste 48 timene og unngå all *uvant* trening de siste 72 timene.

- Gjennomfører styrketreningsprogrammet som er blitt utdelt under hele treningsperioden.
- Registrerer kostholdet i sju dager fordelt på tre perioder; i starten, midtveis, og på slutten av prosjektet.
- Registrering av sykdom og skader og enkel loggføring av styrketrening hver 14.dag
- For kvinnelige deltagere: registrerer menstruasjonssyklus i egen app og rapporterer inn avvik.

Testene som utføres før og etter treningsperioden:

- Høyde, vekt, subjektiv vurdering av opplevd restitusjon og menstruasjonssyklus.
- En kroppsscan (dual-x-ray-absorptiometry [DXA]) som måler din totale muskelmasse i kroppen samt hvor sterkt skjelettet er.
- Muskelvevsprøve i lårmuskulaturen (m. vastus lateralis) etter bedøvelse totalt 3 ganger.
- Muskelstørrelse av samme lårmuskulatur med ultralyd.

Deretter er det en 10 minutters lang oppvarming etterfulgt av 3 forsøk for hver test og med 3 minutter pause mellom hvert forsøk:

- 30 meter sprint (med splittider) og sprint med retningsforandring.
- Kastehastighet.
- Svikthopp og en 3-steg hopp-rekkevidde test («jump & reach»).
- Styrke og power med beinpress og benkpress.

I tillegg vil det gjennomføres et akutt forsøk i slutten av treningsperioden.
Subjektiv grad av opplevd restitusjon og testene muskelvevsprøve og svikthopp utføres rett før en treningsøkt, i tillegg til styrke og elektrisk stimulering av musklene for å måle tretthet i muskulaturen. Deretter vil deltakerne trene en økt med de oppsatte treningsøktene som de har fulgt i treningsperioden. Rett etter treningsøkten vil deltakerne rapporterte subjektiv grad av opplevd anstrengelse før en ny runde med de samme testene som deltakerne gjorde rett før treningsøkten. Testene, med unntak av muskelvevsprøver, vil gjentas 24- og 48-timer etter økten.

Kartlegging av treningsbelastning fra håndballspesifikk trening vil gjennomføres med at hver deltaker spiller håndball med enheter som festes til treningstoppen under aktivitet. Dette vil brukes til å se effekten av styrketrening opp imot treningsbelastningen fra idretten. Vi vil gjøre 3 perioder med målinger på 2-3 uker; i starten, midten og slutten av prosjektet.

Treningsgruppene
Selve intervensjonsopplegget (treningen) utarbeides ut fra erfaring med oppfølging av håndballspillere gjennom Olympiatoppen, innspill fra landslagsteamet, samt tilsvarende program som er brukt i tidligere forskning på lagspillutøvere.

Deltakerne vil bli tilfeldig delt inn i to treningsgrupper. Treningen i den ene gruppa vil bestå av maksimal styrketrening med høy motstand (~70-90 % av 1RM) på ulike styrkeøvelser for bein og overkropp. Imens den andre gruppen to vil trene eksplosiv «power» styrketrening med lavere belastning (20-60% av 1RM) på bein og overkropp, samt plyometrisk trening (sprint- og spenstøvelser) med kroppsvekt. Gruppene vil trene 2-3 ganger per uke under hele prosjektperioden, ved siden av lagtreninger og kamper.

MULIGE FORDELER OG ULEMPER

Mulige fordeler med deltakelse:

- Treningsprogrammene er laget for at du skal oppnå en prestasjonsøkende effekt.
- Du vil få treningsoppfølging og veiledning.
- Du vil få kjennskap til hvordan den spesifikke treningen påvirker deg.
- Du vil få økt kunnskap om din kapasitet og prestasjon relatert til styrke, spenst, hurtighet og power, som normalt ikke er tilgjengelig.
- Resultatene kan inngå i egen treningsplanlegging.
- Du vil bidra til å øke kunnskapen på temaet og fremheve prestasjonsfremmende forskning på håndballutøvere.
- Du vil få mulighet til å stille spørsmål om det du måtte lure på angående trening.
- Du kan få økt kunnskap om idrettsernæring ved å bli invitert til å delta på foredrag

Mulige ulemper med deltakelse:

- Deltakelse i prosjektet vil kreve at du setter av tid til testing og trening
- Trening og testing kan føre til stølhet og oppfattes som ubehagelig/smertefullt i etterkant, og det fører også med seg en viss risiko for skader. Denne risikoen anses imidlertid ikke som større enn ved den treningen du er vant til fra før.
- DXA-kroppsskann medfører en lav røntgenstrålingsdose, men anses ikke som farlig og tilsvarer dosen en utsettes for under en interkontinental flyreise.
- Muskelprøvetaking kan være ubehagelig, selv om huden og bindevevet rundt muskelen bedøves for å minimere ubehag. I om lag et døgn etter muskelprøven opplever man ømhet og stølhet i området rundt snittet. Ømheten vil deretter avta og forsvinner vanligvis i løpet av én-fire dager. Enkelte personer kan få tydelig arrdannelse etter

snittet i huden. Se vedlegg I for bilder av arr etter muskelprøve, og vedlegg II for sårstell etter muskelprøvetagning.

- Elektrisk stimulering av musklene vil få de til å trekke seg sammen og det oppleves som å få et støt. Dette kan oppleves litt ubehagelig, men er helt ufarlig.

DINE RETTIGHETER: FRIVILLIG DELTAKELSE OG RETT TIL Å TREKKE SEG

Det er frivillig å delta i prosjektet. Dersom du ønsker å delta, undertegner du samtykkeerklæringen på side 7. Ved å signere denne samtykkeformen gir du tillatelse til å bruke resultatene til de formål som er beskrevet i dette skrivet. Om du nå sier ja til å delta, kan du senere, når som helst og uten å oppgi grunn, ombestemme deg og trekke deg uten at det har noen konsekvenser for deg. Dersom du trekker deg fra studien, kan du kreve å få slettet innsamlede opplysninger/data, med mindre opplysningene allerede er inngått i vitenskapelige publikasjoner. Det vil ikke være mulig å identifisere deg i resultatene av studien når disse publiseres. Ta kontakt med oss dersom du velger å forlate prosjektet (se side 6 for kontaktinfo).

Dine rettigheter
Så lenge du kan identifiseres i datamaterialet, har du rett til:

- innsyn i hvilke personopplysninger som er registrert om deg, og å få utlevert en kopi av opplysningene,
- å få korrigert eventuelle feil i de opplysningene som er registrert om deg,
- å få slettet personopplysninger om deg, og
- å sende klage til Datatilsynet om behandlingen av dine personopplysninger.

Dersom du har spørsmål til dine rettigheter, kan du kontakte vårt personvernombud:
Johanne Warberg Lavold (johanne.lavold@uia.no, 412 12 048).

HVA SKJER MED OPPLYSNINGENE OM DEG?

Vi vil bare bruke opplysningene om deg til formålene vi har fortalt om i dette skrivet. Vi behandler opplysningene konfidensielt og i samsvar med personvernregelverket.

Opplysninger som registreres om deg er:

- Høyde, vekt, fødselsdato, menstruasjonssyklus på testtidspunkter og avvik i treningsperioden samt subjektive mål av selvopplevd restitusjon og anstrengelse.
- Kosthold i totalt 3 uker
- Maksimal styrke, power, spenst, hurtighet, kroppssammensetning (fettfri- masse, kroppsfett og benmineraltetthet) og biologisk muskelvev
- Trening som gjennomføres utenfor prosjektet

Universitetet i Agder er ansvarlig for all informasjon som samles inn i dette prosjektet. Informasjon om deg vil behandles avidentifisert. Det betyr at vi gir deg et deltakernummer og linker all innsamlet informasjon til dette nummeret. Vi har en kodeliste (ett eksemplar) som kobler navnet ditt til forsøkspersonnummeret. Det er kun prosjektleder (Prof. Truls Raastad) og prosjektkoordinator (Fredrik Tonstad Vårvik) som har tilgang til denne listen. Prosjektet avsluttes 31.12.2025 og da vil kodelisten destrueres, noe som betyr at innsamlet informasjonen er anonymisert og ingen opplysninger kan spores tilbake til deg. Anonymisert innsamlede data vil bli slettet fem år etter prosjektslutt, eller når resultatene er publisert. Deltakerne kan også bli kontaktet på et senere tidspunkt dersom det skulle bli aktuelt med oppfølgingsstudier. De kan velge å takke nei selv om de er med i treningsintervensjonen.

HVA SKJER MED PRØVER SOM BLIR TATT AV DEG?

Muskelprøvene som tas av deg skal oppbevares i en forskningsbiobank tilknyttet prosjektet. Ansvarlig for biobanken er prosjektleder Prof. Truls Raastad. Biobanken opphører ved prosjektslutt. Ved å delta i prosjektet, samtykker du også til at opplysninger om muskeltykkelse, -styrke, samt muskelvev kan overføres til utlandet som ledd i forskningssamarbeid og publisering. Prosjektleder vil sikre at dine opplysninger blir ivaretatt på en trygg måte. Koden som knytter deg til dine personidentifiserbare opplysninger vil ikke bli utlevert. Dersom data overføres til utlandet skal prøvene destrueres ved prosjektslutt eller når resultatene er publisert.

GODKJENT PROSJEKT

Prosjektet vil søke om godkjenning fra Regional komité for medisinsk og helsefaglig forskningsetikk, samt godkjenning for behandling av personopplysninger fra Norsk senter for forskningsdata (NSD). Etter ny personopplysningslov har behandlingsansvarlig UiA og prosjektleder Prof. Truls Raastad et selvstendig ansvar for å sikre at behandlingen av dine opplysninger har et lovlig grunnlag. Dette prosjektet har rettslig grunnlag i EUs personvernforordning artikkel 6 nr. 1a og artikkel 9 nr. 2a, ditt samtykke.

Hvis du har spørsmål knyttet til NSD sin vurdering av prosjektet, kan du ta kontakt med dem på epost: personverntjenester@nsd.no eller på telefon: 55 58 21 17.

FORSIKRING

Alle deltagere er forsikret gjennom Universitetet i Agder, som statlig institusjon, er selvassurandør.

INFORMASJON OM UTFALLET AV PROSJEKTET

Du vil få informasjon om resultatene av studien. Det vil bli gjennomført en presentasjon på et informasjonsmøte for forsøkspersonene i etterkant av studien. Resultatene vil bli publisert i nasjonale/internasjonale vitenskapelige tidsskrift, kronikker og foredrag.

SPØRSMÅL OM PROSJEKTET? TA GJERNE KONTAKT

Prosjektansvarlig/stipendiat Fredrik Tonstad Vårvik
E-post: fredriktv@uia.no / Tlf: 928 54 969

Prosjektleder/Professor Truls Raastad
E-post: truls.raastad@nih.no / Tlf: 23 26 23 28

SAMTYKKEERKLÆRING

JEG SAMTYKKER TIL Å DELTA I PROSJEKTET OG TIL AT MINE PERSONOPPLYSNINGER OG BIOLOGISK MATERIALE BRUKES SLIK DET ER BESKREVET

Sted og dato Deltakers signatur

Deltakers navn med BLOKKBOKSTAVER

Prosjektmedarbeider bekrefter å ha gitt informasjon om prosjektet

Sted og dato Signatur

Rolle i prosjektet

VEDLEGG 1: MUSKELVEVSPRØVE

Bilde 1 → viser tre arr etter tre muskelprøver på
venstre lår (samme sted som denne studien).
Det øverste er 6 måneder gammelt,
de to nederste er 3 måneder gamle.

Bilde 2 under viser to arr etter to muskelprøver på
høyre lår (samme sted som denne studien).
Det øverste arret er 7 år gammelt og det
nederste er 6 måneder gammelt.

Bilde 3 → viser tre arr etter tre muskelprøver på overarm. Det er over 10 år siden muskelprøvene ble tatt.

VEDLEGG 2: SÅRSTELL ETTER MUSKELVEVSPRØVE

Du er nå deltager i et forskningsprosjekt hvor vi har tatt muskelprøver (biopsi) fra låret ditt (m. vastus lateralis). Dette er et lite inngrep som ikke skal ha noen negative følger annet enn sår muskulatur noen dager etter inngrepet. Det kan gjøre vondt/være sårt i kveld når bedøvelsen går ut, og i morgen, men det vil gå over i løpet av en dag eller to.

Det er imidlertid en minimal risiko for infeksjon etter slike inngrep. Vi ber deg derfor om å følge rådene under. Om det skulle oppstå noe av medisinsk karakter som du tror kan settes i sammenheng med forsøket, må du ta kontakt med oss uansett tid på døgnet (se kontaktinformasjon nederst i skrivet).

Det er nå viktig at du tar følgende forhåndsregler slik at sårene dine skal gro godt:

- Bandasjen som er surret rundt låret ditt kan tas av i kveld før du legger deg.
- Hvit plasterlapp og strips skal sitte på én uke. Vi anbefaler at stripsene ikke rives av, men tas av når de løsner fra selve såret. Dersom dette skjer før det har gått én uke, ta kontakt slik at vi kan sette på nye.
- Hold sårområdet tørt. Du bør ikke vaske området ved sårene eller dusje slik at tapen rundt såret blir våt. Vann vil øke faren for infeksjon og det vil også medføre at tapen som skal hold sårflatene sammen, løsner. Du kan dusje, men sørg for at du ikke får vann i nærheten av sårene. Dersom du skal dusje, vær forsiktig og bruk plastfolie/"gladpack", vanntette plaster eller lignende for å hindre vann å trenge gjennom plasterlappen.

For å sikre at arrene blir så lite synlige som mulig, anbefaler vi å smøre arrene med høy solfaktor ved soleksponering.

Kontaktpersoner ved Universitetet i Agder:
Truls Raastad: 91 36 88 96
Fredrik Tonstad Vårvik: 928 54 969