Force velocity profiling for athletes: Performance assessment and individualized training prescriptions.

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UiA University of Agder

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Performance assessment and individualized training prescriptions

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Preface

This dissertation describes the author's research conducted at the *University of Agder (UIA)* In collaboration with the *Norwegian Olympic and Paralympic Committee and Confederation of Sports*, the *Norwegian School of Sport Sciences,* and the *Norwegian Sports Medicine Centre* (Idrettens Helsesenter).

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As I stand at this juncture, reflecting upon the myriad experiences, learnings, and collaborations that have paved the path to this dissertation, I'm filled with gratitude. To all those named and the countless others who have played a role, big or small, in this journey — I cherish our collaborations and remain hopeful for countless more in the years ahead.

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List Of Papers

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Summary

Background: The concept of force-velocity (FV) profiling is inspired by the fundamental properties of skeletal muscles, where there is an inverse relationship between force and velocity. The measurement of force and the corresponding velocity during varying loads have been conducted since the start of the 20th century. Due to rapid advances in technology, devices that can measure forces and velocities in a variety of movements have increased rapidly in recent years. As a result, FV profiling has gained popularity among coaches, athletes, and scientists as a tool for performance assessment and individualized training prescriptions.

Purpose: The purpose of this Ph.D. thesis was to investigate the use of force-velocity profiling as a tool for performance assessment and individualized training prescriptions in athletes. To achieve this aim, three experimental studies were conducted, each addressing a specific research question. Study I aimed to assess the reliability and agreement of commonly used measurement equipment for evaluating force-velocity profiles in well-trained and elite athletes. Study II investigated the effectiveness of an individualized training approach based on FV-profiling on jumping performance in well-trained athletes. Lastly, Study III aimed to investigate whether a placebo effect is present when participants are told they are receiving "optimal training" compared to "control training." The hypothesis was that FV-variables obtained from different measurement equipment would not be consistent, and the reliability would depend on the equipment and procedures used. The thesis also hypothesized that individualized training based on FV-profiling would lead to greater improvements in jump height compared to traditional power training. Additionally, a placebo effect was anticipated when participants were informed, they were receiving "optimal training."

Methods: In total, 216 participants were initially included for testing across all three studies. *Study I*: Involved 100 participants (male and female) ranging from world-class Olympic medalists to club-level athletes. The study design involved physical testing of participants four times, with the first two testing timepoints separated by approximately one week, followed by a training period of two to six months, and the last two timepoints separated by approximately one week. The data was collected from various Olympic training and testing facilities. The testing protocol consisted of a series of squat jumps (SJ), countermovement jumps (CMJ), and a leg press test with incremental loads. The FV-relationship was derived from a force plate, a linear position transducer encoder, and a flight-time calculation method. To determine the FV-variables, the average force and velocity measurements for each test were fitted with linear regression, resulting in theoretical maximal force (F_0), velocity (V_0), power (P_{MAX}), and the slope of the FV profile (S_{FV}). *Study II*: A 10-week training intervention was carried out on 46 national-level team sport athletes (20 ± 4 years, 83 ± 13 kg) from ice-hockey, handball, and soccer. To develop a theoretical optimal squat jump (SJ)-FV-profile, SJ with five different loads (0, 20, 40, 60, and 80 kg) was performed. Based on the participants' initial FV-profile, athletes were randomly assigned to train toward, away, or independently (balanced training) of their initial theoretical optimal FV-profile, utilizing training material that was the same across groups in terms of sets x repetitions but changed in relative loading to target different parts of the FV-profile. The athletes were assessed in 10 and 30 m sprints, SJ, and CMJ, one repetition maximum (1RM) squat, and a leg-press power test before and after the intervention. *Study III*: 70 male and female Athletes were recruited for a 10-week training intervention. Participants were informed that they were either in the individualized training program based on their force-velocity profile (Placebo) or the control group (Control). Despite the different allocations, both groups followed the same workout routines on average. The testing protocol included CMJs with progressively heavier weights, 20-meter sprints, 1RM back squats, and leg-press tests. Ultrasound measurements were taken using a brightness mode (B-mode) ultrasonography apparatus to measure the resting muscle thickness of the *m. rectus femoris*. The SETS scale (Stanford Expectations of Treatment Scale) was used to evaluate positive and negative treatment expectations toward the intervention.

Results: In *Study I*, although individual FV-profiles displayed strong linearity (R2>0.95), yet the S_{FV} was unreliable for all measurement methods during vertical jumping (coefficient of variation (CV): 14–30%, interclass correlation coefficient (ICC): 0.36–0.79). Further, only the leg press exercise displayed acceptable reliability for all four FV-variables (F_0, V_0, P_{MAX}, S_{FV}) (CV: 3.7-8.3%, ICC: 0.82-0.98). While F_0 and P_{MAX} demonstrated a relative agreement across measurement methods (Pearson r: 0.56–0.95, Standard Error of Estimate [SEE] %: 5.8–18.8), V_0 and S_{FV} showed lower to no agreement across methods (r: -

0.39–0.78, SEE%: 12.2–37.2). In *Study II*, the results indicated no significant group differences in any of the performance measures. Changes toward the optimal SJ-FV-profile had a negative correlation with changes in SJ height (r = -0.49, p < 0.001). Changes in SJ-power had a positive correlation with changes in SJ-height (r = 0.88, p < 0.001) and CMJ-height (r = 0.32, p = 0.044), but no significant correlation with changes in 10 m (r = -0.02, p = 0.921) and 30 m sprint time (r = -0.01, p = 0.974). Small to trivial changes in 1RM squat (2.9%, 4.6%, and 6.5%), 10 m sprint time (1.0%, -0.9%, and -1.7%), 30 m sprint time (0.9%, -0.6%, and -0.4%), CMJ height (4.3%, 3.1%, and 5.7%), SJ height (4.8%, 3.7%, and 5.7%), and leg-press power (6.7%, 4.2%, and 2.9%) were observed in the groups training toward, away, or irrespective of their initial theoretical optimal FV-profile, respectively. In *Study III*, the Placebo group demonstrated a significant increase in 1RM squat compared to Control (5.7 ± 6.4% vs. 0.9 ± 6.9%, [0.26 vs 0.02 Effect Size], Bayes Factor: 5.1 [BF 10], p = 0.025). Additionally, the Placebo group showed slightly higher adherence to the training program compared to Control (82 ± 18% vs. 72 ± 13%, BF10: 2.0, p = 0.08). After controlling for adherence, the difference in 1RM squat between the groups remained significant (p = 0.013), while no significant differences were observed in the other measurements.

Conclusions: *Study I*, Test-retest reliability of the FV-profile can be affected by various factors, including biological, technical, and methodological variation. However, what sets it apart from other performance assessments is the distance/degree of extrapolation to the FV-intercepts, which also plays a crucial role in its reliability. Our data shows that when there is a 5-10% variation in individual jumps, V_0 and S_{FV} cannot be accurately measured, regardless of the measurement method used. It is important to be aware of these limitations when assessing FV-profiles, especially in jumping tasks. For improved accuracy of FV-profile assessments, efforts should be made to reduce variation in jumping performance and/or assess loads closer to the FV-intercepts. *Study II* challenges the notion that training toward an optimal SJ-FV-profile is beneficial for improving athletic performance. Results showed no significant differences in SJ height, CMJ height, 10 and 30 m sprint time, 1RM strength, or leg-press power between participants who trained toward, away from, or balanced irrespective of their initial FV-profile. These results call into question the use of FV-profiles for guiding individualized training prescriptions in athletes. Instead, the focus should

be on improving power across the entire FV continuum rather than solely attempting to correct a theoretical FV imbalance. *Study III* provides novel evidence that believing to receive optimal training instead of a generic training program may induce a placebo effect in sports and exercise training interventions. These findings imply that the placebo effect could play a significant role in the outcome variances of training interventions that lack a placebo-controlled design. The findings of this dissertation emphasize the importance of carefully selecting measurement equipment, exercises, and procedures when using force-velocity profiling for performance assessment. Additionally, the thesis highlights that individualized training based on force-velocity profiling may not always result in significant improvements in performance outcomes. Therefore, coaches and athletes should be cautious when using FV profiling as the sole determinant for individualized training programs. Finally, the presence of a placebo effect in training interventions indicates the need for placebo-controlled designs in future research.

Abbreviations

1RM	One-repetition maximum
ANCOVA	Analysis of covariance
ANOVA	Analysis of variance
BF	Bayes factor
B-mode	Brightness mode
CI	Confidence interval
CMJ	Countermovement jump
CV	Coefficient of variation
ES	Effect size
F_0	Force intercept of the force-velocity relationship
FV	Force-velocity
FV_{IMB}	Force-velocity imbalance
FV-profile	Force-velocity profile
GEN	Generic training group
ICC	Intraclass correlation coefficient
IMB	Imbalance training group
IND	Individualized training group
P_{MAX}	Maximum power of the force-velocity relationship
RFD	Rate of force development
RIR	Reps in reserve
RM	Repetition maximum
RMSE	Root mean square error
RPE	Rating of Perceived Exertion
SD	Standard Deviation
SEM	Standard error of measurement
SETS	Stanford Expectations of Treatment Scale
S_{FV}	Slope of the force-velocity relationship
SJ	Squat jump
SPSS	Statistical Package for the Social Sciences
V_0	Velocity intercept of the force-velocity relationship

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1 Introduction

1.1 Rationale for the Thesis

Improving human performance has been a long-standing pursuit throughout history, from ancient civilizations that valued physical fitness for practical and cultural reasons. This goal has continued throughout history and is now being explored through improvements in technology and science that are pushing the limits of human performance. Force-velocity (FV) profiling has recently gained popularity among coaches, athletes, and scientists as a tool for performance assessment and individualized training prescriptions. The concept of FV profiling is inspired by the fundamental properties of skeletal muscles, where there is an inverse relationship between force and velocity (Alcazar, Csapo et al. 2019).

The measurement of force and the corresponding velocity during varying loads have been conducted since the start of the 20th century, described in the literature as early as 1922 by AV Hill (Hill 1922). However, such measurements have been confined to enthusiastic scientists and institutions with large labs up until recently (Jaric 2015, Alcazar, Csapo et al. 2019). Due to rapid advances in technology, devices that can measure forces and velocities in a variety of movements have increased rapidly in the last years (Pérez-Castilla, Rojas et al. 2019). Consequently, the interest and relevance of measuring the FV relationship have increased in parallel with these rapid technological advancements (Giroux, Rabita et al. 2015, Meylan, Cronin et al. 2015, Feeney, Stanhope et al. 2016, Jiménez-Reyes, Samozino et al. 2017). Commonly in the literature, dating back to the years of AV Hill, the measurement of force and velocity has been referred to as the force-velocity relationship. In recent years, the term “profiling” has been added, usually in the field of sports science and strength and conditioning, when we are referring to the FV relationship in the context of athletic performance assessment (Jaric 2015).

The overarching aim of the thesis is to explore the use of force-velocity profiling in athletes. The following chapters will look at the background of the measurements of the force-velocity relationship, its physiological basis, and how it relates to the mechanical output in human movements. We will further look at recent developments in technology to “profile” athletes’ force-velocity relationships as well as methods to individualize training. The goal is to guide the reader through the current knowledge and the lack thereof, which form the basis for the research projects included.

1.2 Skeletal Muscle's Intrinsic Force-Velocity Characteristics

A fundamental concept in muscle physiology is the force-velocity relationship, which describes the relationship between the force generated by a muscle fiber and the velocity at which it shortens. This chapter will briefly discuss the historical and physiological background of the intrinsic force-velocity characteristics of skeletal muscle.

One of the earlier modern researchers in the field was Giovanni Aldini, who demonstrated that electrical stimulation of muscles could produce contractions (Fulton and Cushing 1936). Over the years, many researchers contributed to our understanding of the physiological properties of muscle fibers. In the early 20th century, Hill and his colleagues, amongst other researchers, conducted a series of experiments to study the relationship between muscle forces and shortening velocities. In an initial study in 1922, performing several elbow flexions against different resistances, Hill found that the force generated by the muscles decreased with increasing velocity (Hill 1922) (See Figure 1). One of the earlier hypotheses proposed to explain the decrease in force with increasing velocity was the influence of the viscosity of the contractile material within the muscles. As the velocity of the contraction increased, the viscous resistance would then increase, according to this rationale (Hill 1922). Additionally, they speculated whether neural mechanisms also would influence the FV-relationship they observed. The earlier studies in humans were followed up by several studies in isolated frog muscles (Gasser and Hill 1924, Levin and Wyman 1927, Hill 1955). In these studies, the muscles were attached to a lever system while being electrically stimulated, measuring the mechanical response (Hill 1938).

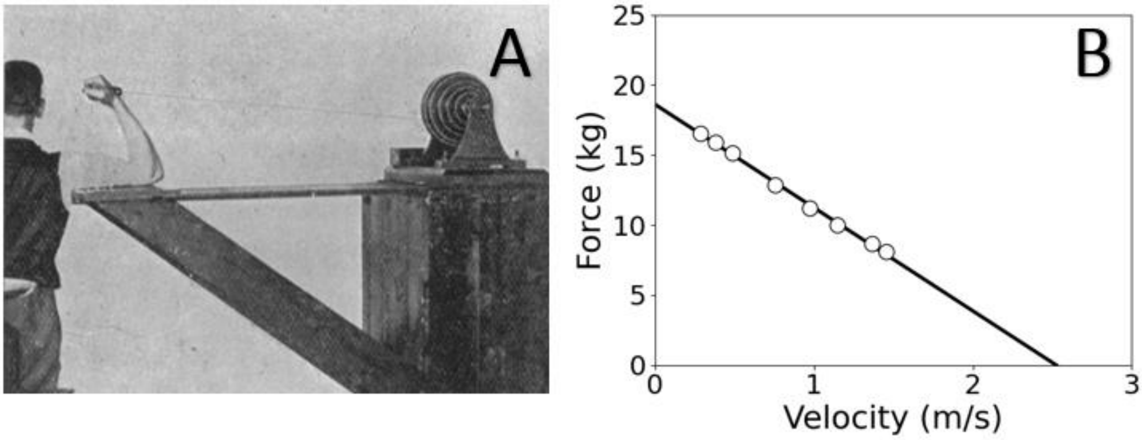

Figure 1. *A: Ergometer setup utilized by Hill in 1922 to measure the mechanical work executed by the elbow flexor muscles against a flywheel (Hill, 1922). B: The relationship between force and velocity from the elbow flexors in the experiment by Hill 1922, recreated from the calculations presented by Alcazar 2019.*

Consequently, in these experiments, mechanisms related to the central nervous system could be excluded. Like the experiment in humans, the force decreased with increasing velocity, but the shape of the relationship changed from linear to a non-linear relationship (Hill 1938). Building on these previous experiments and with more accurate measurement techniques, Hill conducted an experiment outlining an equation he believed described the FV-relationship of muscles across humans and other species. Hill's model was significant because it was the first to consider both the material properties of muscle and the possible chemical reactions that influence muscle contraction. (Equation 1):

Equation 1:

$$(F + a)(V + b) = (F0 + a)b$$

The variables in the equation are as follows: F represents force, V represents velocity, F_0 represents isometric force, a is a constant that indicates the amount of heat generated per unit of shortening with the dimensions of the load, and b is a constant that expresses the rate of increase in energy per unit of decrease in load with the dimensions of velocity (Hill 1938). In Hills' experiments, the same hyperbolic force–velocity relationship could be derived from heat measurements, and the constant a was found to closely match an empirically derived thermal constant of shortening heat. Consequently, the equation suggested that the mechanics of muscle contraction is closely related to the muscle's energy metabolism. However, it was later shown that this hypothesized constant depended on shortening velocity and load and therefore was not a constant (Hill 1964). As Hill originally believed, it appeared that the force–velocity behavior of a muscle was not an unfiltered expression of energetic events occurring within the muscle (Hill 1938, Hill 1964).

Hill's model represented an important advancement of knowledge regarding the force-velocity relationship. However, it was not without flaws, and as with any scientific model, it has been refined and improved upon over time. Despite its somewhat accurate representation of force–velocity relationships, the equation has been historically regarded as merely empirical and devoid of insight into the molecular mechanism of contraction (Sugi and Chaen 2016). Hugh Huxley, one of the pioneering researchers in muscle physiology, advanced our understanding of the force-velocity relationship. Utilizing the novel technology of electron microscopy, he, along with Jean Hanson, studied the muscle fiber structure during contraction and relaxation. Their findings laid the groundwork for the sliding filament theory, as presented in their 1954 paper (Huxley and Hanson 1954). Further investigations revealed that actin and myosin filaments slide past each other during muscle contractions. A key observation was the direct relationship between the force produced by a muscle and the number of myosin-actin cross-bridges formed during contraction. These insights proved invaluable in comprehending the force-velocity relationship. The sliding filament theory could indeed predict that as contraction velocity increased, the force generated would decrease, due to the reduced time available for forming myosin-actin cross-bridges (Hitchcock-DeGregori and Irving 2014).

In the later years, numerous researchers have built upon the previous models and further our understanding of the force-velocity relationship. Today, the most widely accepted explanation of the force-velocity relationship is based on the kinetics of the cross-bridge interaction between actin and myosin (Herzog 2014). This cross-bridge interaction involves a series of chemical interactions between the actin and myosin protein that causes the generation of force. The hydrolysis of ATP to ADP causes releases of energy which cause the power stroke of the myosin head upon the actin filaments. Specifically, the ATP molecules bind to the myosin heads, causing it to detach from the actin, resetting for another cycle of cross-bridge formation and force generation (Sugi and Ohno

2019). The amount of force the muscle can generate is then proportional to the number of cross-bridges formed. When the velocity of the contraction increases, fewer cross-bridges can be formed, which results in lower force output. Hence the inverse relationship between the two. Followingly, the ATPase activity of the muscle, i.e., the rate at which ATP is hydrolyzed, determines the rate of decrease in force with increasing velocity (Sugi and Ohno 2019).

Together, the knowledge regarding the skeletal muscle's intrinsic Force-Velocity Characteristics has seen significant development in the last decade. The observed relationship appears to be a product of a complex interplay between actin and myosin proteins, their cross-bridge formation, and the muscle's metabolism. In the next chapter, we will further look at how this intrinsic muscular relationship relates to the measurement performed in humans and multi-joint movements.

1.3 *In vivo* Force-Velocity Mechanical Output

The intrinsic force-velocity relationship and its characteristics form a fundamental aspect of muscle physiology. However, when examining this relationship *in vivo*, particularly within the context of humans, numerous additional factors must be taken into account. When interpreting the force-velocity relationship measured in athletic contexts, it becomes crucial to thoroughly understand and consider all the variables that can impact the observed relationship.

And a growing interest has emerged in describing muscle function in complex multi-joint tasks (like jumping, squatting, bench-pressing etc. (Gülch 1994, Jaric 2015). This ranges from assessing the mechanical output of older individuals to the top-performing athletes (Alcazar, Rodriguez-Lopez et al. 2018, Morris, Weber et al. 2020, Simpson, Waldron et al. 2020). It is widely recognized in the literature that the FV relationship is an important characteristic of muscle function; however, there is less agreement regarding the underlying mechanisms of the observed multi-joint force-velocity mechanical output (Jaric 2015, Sugi and Ohno 2019). In the literature, the terminology is usually similar when describing multi-joint force-velocity relationships and intrinsic muscle fiber force-velocity relationships. Such interchanging use of terminology might indeed be the root cause of some of the disagreement in the literature. Several factors contribute to the difference between the two different force-velocity relationships, which we will discuss in the following paragraphs.

The human skeletal system is a complex interplay between the nervous system, the musculoskeletal system, the mechanical demands of the task at hand, and the coordination between all of them (Duchateau and Enoka 2008, Xu, Zhang et al. 2022). So, when we move from the isolated single muscle fiber to the multi-joint mechanical output, numerous additional factors come into play (Jaric 2015, Sugi and Ohno 2019). Interestingly, the force-velocity relationship has consistently been observed across a wide variety of movement tasks ranging from simple single joint contraction to complex tasks such as jumping, throwing, and even sprint running (Thorstensson, Grimby et al. 1976, Van Den Tillaar, Ettema et al. 2004, Zivkovic, Djuric et al. 2017). Across all the different conditions, the force consistently decreases with increasing velocity. However, both the rate at which force decreases with increasing velocity and the shape of the relationship varies across the different tasks (Figure 2) (Alcazar, Navarro-Cruz et al. 2018). Highlighting the complexity of measuring the FV relationship *in vivo* and all the potential factors that come into play.

One of the factors influencing the *in vivo* FV relationship is the bone structure, tendons, and ligaments. For example, the compliance and release of elastic energy during movements and muscle contraction (Roberts 2002). Another factor that comes into play is neural control of both the muscle contractions in the combination of the coordination of especially the more complex movement tasks such as sprint running (Gittoes and Wilson 2010). Further, other factors such as muscle architecture, muscle fiber type distribution, and muscle activation pattern also likely contribute to the observed *in vivo* Force-Velocity relationship (Aagaard, Simonsen et al. 2002, Morales-Artacho, Ramos et al. 2018). Muscle architecture, i.e., the length of the muscle fibers as well as the orientation of the fibers within the muscle belly, can affect the amount and direction of the force output during movement (Lieber and Fridén 2000, Morales-Artacho, Ramos et al. 2018). It is also known that the composition of muscle fiber types influences the FV relationship, as the different types have differing contractile properties (Thorstensson, Grimby et al. 1976). Additionally, the muscle activation patterns, influenced by motor learning and fatigue, can influence the recruitment of different motor units within the muscle (Freund

1983, Kallenberg and Hermens 2008). The length-tension relationship of the muscle is also an important factor to consider. When the muscle shortens or lengthens, the number of cross-bridges able to form increases or decreases, influencing the force output and causing the length-tension relationship to be shaped like an inverted – U shape (Ter Keurs, Iwazumi et al. 1978). Hence, the length-tension relationship also likely comes into play when measuring the force-velocity relationship *in vivo*.

Another large factor influencing the *in vivo* and multi-joint force-velocity relationship is the biomechanics of the movement at hand (Winter 2009, Bobbert 2012, Jaric 2015). Encompassing everything from joint angles, moment arms, and segmental dynamics to the interplay between the agonist and agonist muscle activation. Such factors can all contribute to different multi-joint force-velocity relationships across movements, although the intrinsic-force velocity relationship might be constant (Jaric 2015). For example, with varying joint angles, the length-tension relationship also varies (Chang, Su et al. 1999). In multi-joint movements, the joint angle also influences the mechanical advantage of the muscle, which causes the torque output to be non-linear with the force exerted by the muscle (Biewener, Farley et al. 2004). Additionally, the mechanical advantage of the muscle is not only influenced by joint angle but also by the insertion and origin of the muscle (Biewener and Roberts 2000). Segmental dynamics, referring to the interaction between different body segments during movement, can also influence the FV relationship (Bobbert 2012). For example, in complex dynamic tasks such as throwing, running, or jumping, the sequential motion of the involved limbs all contribute to the final velocity and force measured in the movement.

It's clear that numerous factors are involved when measuring the multi-joint and the *in vivo* force-velocity relationship, and it’s fascinating that the force-velocity relationship is still observed across such a wide variety of movements. However, one of the most apparent differences between the FV-relationship observed in isolated muscle fibers and the *in vivo* FV-relationship is the shape of the FV curvature (Alcazar, Csapo et al. 2019). The most common shape reported in multi-joint movements is a linear relationship. And in isolated muscle fibers, the most common shape to describe the relationship is the hills-hyperbolic curvilinear relationship and, in more recent years, the double-hyperbolic shape (Alcazar, Csapo et al. 2019).

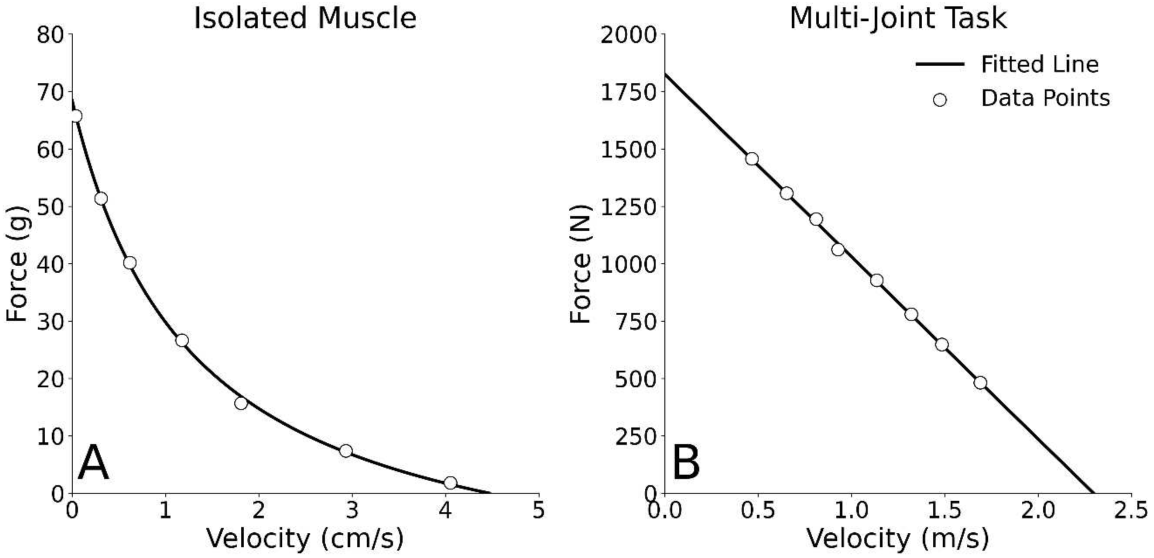

Figure 2*. A: Hyperbolic Force-Velocity Relationship of a frog's sartorius muscle, from Hill's 1938 study recreated using ImageJ software. B: Force-Velocity Relationship from a human in a Multi-joint Leg press task, derived from data generated in the course of the current thesis work.*

The correct shape to describe the force-velocity relationship has indeed been a common topic of discussion in the literature. To this end, in 1976, Edman et al. conducted a study investigating the shape of the FV-relationship, revealing the double-hyperbolic relationship to be a better fit compared to the originally used Hills model (Edman 1976). For a more in-depth description of the topic, a comprehensive review of the topic was published in 2019 by Alcazar et al. (Alcazar, Csapo et al. 2019). Shortly, the double-hyperbolic relationship is thought to be a more accurate description of the kinetic properties of the cross-bridge formation compared to the hyperbolic model. This distinction becomes particularly evident at very high forces, where deviations from the hyperbolic relationship are observed (> ~80% of the maximal isometric force), probably due to an attenuation of the force produced by each cross-bridge formed, although the number of cross-bridges increases. Additionally, there also appear to be slight deviations from the hyperbolic shape at higher velocities/ lower forces (< ~5% of the maximal isometric force). There are fewer data and experiments explaining this deviation; however, it is speculated to be caused by a calcium-independent regulatory mechanism of muscle contraction (Alcazar, Csapo et al. 2019).

Following the last decade’s research into the molecular mechanisms of muscle contraction and muscle physiology, there is now a greater agreement in the literature regarding the shape of the isolated- muscle fibers’ force-velocity shape (Alcazar, Csapo et al. 2019). However, as mentioned above, the *in vivo* force-velocity relationship shape is influenced by a myriad of factors independent of the molecular mechanisms. Such complexity might be part of the reason the shape of the *in vivo* FV relationship is less agreed upon and is still commonly discussed and explored in the literature (Alcazar, Csapo et al. 2019, Rivière, Morin et al. 2021).

Several studies have investigated the shape of the *in vivo* force-velocity relationship (Bobbert 2012). The most used description is the linear – shape, where earlier experiments speculated that the linearity might be caused by central neural inhibitions at higher velocities (Wickiewicz, Roy et al. 1984). However, this hypothesis has been tested and disregarded in more recent experiments, where muscle contractions have been superimposed by electrical stimulation, which then rules out the neural inhibition hypothesis (Westing, Seger et al. 1990). Another reason for the commonly observed linear relationship is argued to be caused by the lack of experimental points across a wide enough range of loads (Alcazar, Navarro-Cruz et al. 2018). Further, there appear to be differences between the FV-relationship observed in single-joints and multi-joint movements. When moving from single-joint to multi-joint, the complexity of the measured relationship increases (Alcazar, Csapo et al. 2019). Mainly, several important biomechanical factors come into play, such as segmental dynamics, variation in joint angles, and mechanical advantage, as mentioned earlier (Bobbert 2012). Interestingly, considering these limitations, recent studies have measured the multi-joint FV profile when trying to control for these factors, primarily by measuring data points at a wide range of loads, in addition to measuring the force and velocity output at a specific joint angle, instead of averaging across the entire range of motion. Indeed, the researchers found that the shape of the FV-relationship then revealed the double-hyperbolic shape also in multi-joint movements (Alcazar, Navarro-Cruz et al. 2018). Following up on these experiments, the authors have conducted experimental training studies, showing that the linear extrapolation fails to accurately detect true changes in the FV relationship at higher velocities/low forces. Only when exceeding 45% of the force intercept did the linear extrapolation adequately detect the training adaptations (Alcazar, Cornejo-Daza et al. 2021). On the other hand, several studies that also have used a large range of loads have rather found a linear fit to better represent the FV data than the hyperbolic – or double hyperbolic fit (Rivière, Morin et al. 2021). The cause for these discrepancies is not obvious, but several possible explanations exist. For example, the resistance utilized, and the method of measurement might both influence the results. In the study by Alcazar, which found the multi-joint FV relationship to be non-linear the subjects first performed vertical squats, and then horizontal "roller" squats to obtain higher velocity measurements (Alcazar, Cornejo-Daza et al. 2021). In such a case the movement patterns, resistive properties as well as measurement method all slightly vary across attempts. Which again could potentially influence the shape of the FV relationship. Oppositely, a study by Rivière et al, used a custom-made ergometer, consisting of a friction-loaded leg press motion, keeping the measurement method and movement pattern identical across loads (Rivière, Morin et al. 2021). In this study, the FV relationship revealed a linear shape. Further, a study by Bobbert, showed that the FV relationship in a simulated leg press task was linear (Bobbert 2012). In this experiment, both the movement pattern and measurement were constant across loads, as well as using a wide range of loads. Hence, ruling out these confounding factors. The experiment was concluded with the observation that the linearity of the multi-joint FV relationship could be explained by segmental dynamics (Bobbert 2012).

Taken together, the *in vivo* force-velocity relationship is a complex interplay of numerous factors ranging from muscle architecture, neural control, biomechanics, and the movement task used to measure it. All in addition to the actual intrinsic force-velocity properties of the isolated single muscle fibers (Alcazar, Csapo et al. 2019). Consequently, the shape of the force-velocity relationship then changes according to how we measure it. It is broadly agreed upon that the single fiber FV relationship follows a double hyperbolic shape. As we move to *in vivo* measurements, the complexity of factors influencing the FV relationship increases (Alcazar, Csapo et al. 2019). Most commonly in the literature, the hyperbolic shape is used for single-joint movements, and the linear shape is used for multi-joint movements. However, as discussed, the shape will vary according to how the measurements are taken and according to how many factors we are able to control for (i.e., range of loads, consistent movement pattern, etc). In practice, the type of relationship used to fit the measured data will eventually come down to what the practitioner is looking to achieve with the measurements and how the data is interpreted. It is clear that more research is needed to elucidate several unanswered questions regarding the relationship between the single fiber intrinsic-force-velocity properties and the *in vivo* fore-velocity profiles used in practice. Nevertheless, in the following chapter, we will look more into how the *in vivo* – force velocity relationship is commonly used in practice for athletic performance assessments.

1.4 Athletic Performance Assessment

The measurement of the force-velocity relationship can be performed in most single and multi-joint movements. For example, as we have seen earlier, the bicep-curl is one of the first exercises where the force-velocity relationship was measured in humans (Hill 1922). Recently, measurements of the lower limbs, specifically in jumping, have gained considerable attention for athletic performance assessments (Jaric 2015, Morin and Samozino 2016). Lower limb muscular capacity and jumping ability have been of interest to researchers for a long time due to their close link with athletic performance (Vescovi and McGuigan 2008, Suchomel, Nimphius et al. 2016).

Previously, the measurement of force-and velocity in jumping required expensive equipment. To measure force, one needs a force plate and, ideally, a 3D motion capture system to measure the velocity (Bosco, Ito et al. 1982, Williams, Chapman et al. 2019). Both alternatives have been constrained to the big labs for a long time. However, in recent years, force plates have become more commonplace. Additionally, equipment like linear transducers, and accelerometers, amongst others, have made it easier to measure force and velocity in the field (Giroux, Rabita et al. 2015).

Today, athletes can perform maximal efforts against different loads while measuring force and velocity during multi-joint movements such as squats, bench presses, or jumping (Zivkovic, Djuric et al. 2017). By measuring the force and velocity output in such a test, one typically uses a linear regression equation to get the individual FV profiles. A linear force-velocity profile is indeed convenient as it is then possible to extrapolate the theoretical maximal force (F_0), velocity (V_0), and power (P_{max}) and calculate the slope of the FV-relationship (S_{FV}) within one test with relatively few data points (See Figure 3) (Jaric 2015).

Regarding the shape used to fit the FV profile data and its limitations, see the previous chapter.

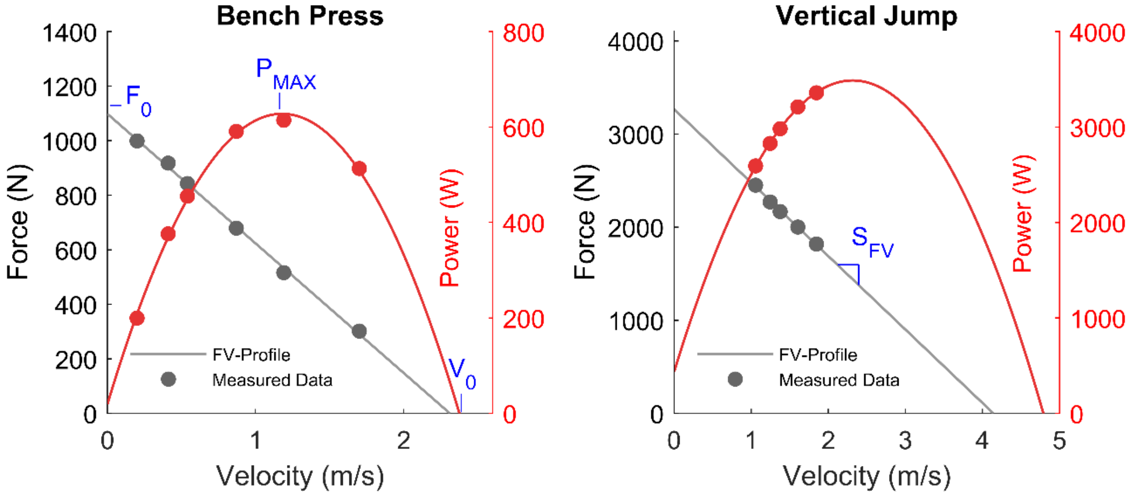

Figure 3. *Example Force-Velocity Profiles from the Bench-press and Vertical Jumping task. Illustrating the commonly used variables: Theoretical maximal force (F_0), velocity (V_0), power (P_{MAX}), and the slope of the FV-profile (S_{FV}). Data obtained from the present thesis.*

The FV variables (F_0, V_0, P_{MAX}, S_{FV}) obtained from a single FV-test in athletes have several practical advantages indeed compared to other assessment methods (Morin, Jiménez-Reyes et al. 2019). For example, calculating P_{MAX} from the FV-relationship can be argued to be a more accurate assessment of maximal power output compared to traditional one-load assessments. As we usually do not know what loads the apex of the power output occurs, the extrapolations from the FV profile are then very convenient (See the example Figure 3 above, where the apex of the power curve occurs outside the measured data range). Similarly, there is no need for concern regarding variations in the load that maximizes power when utilizing extrapolations derived from the FV profile (Morin, Jiménez-Reyes et al. 2019). For example, in Figure 3, we can see that the apex of the power curve from the bench press occurs at load two from the right (corresponding to 40kg in this example). However, after a training intervention, this might change. Or for another individual, it is usually different. Hence, when we use the extrapolations to P_{MAX}, there is no need for concern about fluctuations in the load that maximizes power. Neither whether it is different across individuals. It's worth noting, as was the case in the previous chapter that there are some terms in this context that may require further clarification. Specifically referring to the use of the term power regarding the variable P_{MAX}. When we measure the mechanical output in a complex multi-joint movement, the power we measure refers to the work rate applied to the external load or the center of mass during the movement, which is not the same as the internal power generated by the muscles (Knudson 2009). Hence, the external mechanical power variable P_{MAX} is inherently task-specific and influenced by a variety of factors such as joint angles, coordination, muscle activation patterns, and biomechanical constraints. As a result, the interpretation of such measures of power should be interpreted with that in mind, where the muscle's intrinsic power-generating capacity is not the only factor influencing the measured output. Nevertheless, in practice, the use of the variable P_{MAX} has shown to be a convenient and practical way to assess the external mechanical power output in a variety of movements using the FV profiles (Driss, Vandewalle et al. 1998, Marcote-Pequeño, García-Ramos et al. 2019, Baena-Raya, García-Mateo et al. 2022).

Further, the F_0 intercept is shown to be closely related to traditional measures of maximal strength, such as the one repetition maximum (1RM), making it possible to assess maximal strength capacities without the need to do an additional 1RM test (Morin and Samozino 2018). Although it is not the exact same construct as either an isometric contraction or the 1RM, it is an indication of maximal force-generating capacity (Morales-Artacho, Ramos et al. 2018). There have been conducted numerous studies comparing either the F_0 intercepts or other estimations based on the FV profile towards the real 1RM (McBurnie, Allen et al. 2019, Hughes, Peiffer et al. 2020, Thompson, Rogerson et al. 2021). Generally, there is a good agreement between the two. However, in a study comparing the F_0 intercept toward a maximal isometric contraction, there were large differences (Šarabon, Kozinc et al. 2020). Such findings make a lot of sense, as the measured force data is from dynamic contractions, averaging the force over a larger range of motion, whereas the isometric contraction can only be performed in one specific position. Additionally, recent studies have shown that the linearity of the FV-relationship tends to deviate from its apparent linearity close to the F_0 intercept (Alcazar, Csapo et al. 2019). Hence, it is important to understand the F_0 intercept as nothing more than what it is, a practical extrapolation reflecting maximal force-generating capacity. Not as a measure of isometric strength, nor a 1RM. Interestingly, a recent study comparing the F_0 intercept towards the 1RM, in agreement with the literature, found both to be highly correlated but also found that the F_0 intercept was more reliable across testing sessions (Larsen, Loturco et al. 2023). Although the F_0 intercept has several limitations, as discussed above, the 1RM test also has limitations. For example, one is dependent on increasing the load in a gradual manner to hit the maximal load while both making sure the participant does not get fatigued and attempting a couple of heavy loads to get ready for the max attempt (Grgic, Lazinica et al. 2020). Hence, the use of F_0 as a substitute for the 1RM might indeed be a practical and reliable measure of maximal force-generating capacity.

As we have seen, the F_0 and P_{MAX} variables from the FV profile have several advantages compared to other methods. Interestingly, the extrapolated V_0 and S_{FV} is a unique aspect of the FV-profile. The V_0 is theorized to represent an athlete's force-generating capacity at high velocities (Morin and Samozino 2016). Additionally, the slope of the FV profile (S_{FV}) has been recently theorized to represent the ratio of an athlete’s force-generating capacity at high vs low velocities (Morin and Samozino 2016). Consequently, it has then been suggested to be used as an index for guiding training prescriptions (We will get more into the details of this aspect in the next chapter). Followingly, one gets a lot of useful information about the athlete’s performance, in a convenient and time-efficient manner by measuring the FV profile (Driss, Vandewalle et al. 1998, Samozino, Rejc et al. 2012, Samozino, Edouard et al. 2014, Jiménez-Reyes, Samozino et al. 2017, Marcote-Pequeño, García-Ramos et al. 2019, Baena-Raya, García-Mateo et al. 2022).

Consequently, FV profiling has received increasing attention as a tool for athletic performance assessment. However, the development of methods and equipment to measure FV profiles advances faster than in the scientific literature. Hence, several questions remain unanswered and should be investigated. Numerous different methods and equipment for assessing individual FV profiles exist, with little knowledge of the reliability and validity of these methods (Giroux, Rabita et al. 2015). When analyzing data from top athletes, test reliability is crucial. Additionally, a variety of tools and methods (such as force plates, linear position transducers, pneumatic resistance apparatus, accelerometers, and calculation methods) are used to measure the lower limb FV-variables, but little importance has been given to how well these tools and methods agree with one another (Giroux, Rabita et al. 2015).

There have been some investigations into the different methods and equipment to measure the FV profiles, but most are performed in non-athletic populations or do not look at between-day reliability (Giroux, Rabita et al. 2015, Meylan, Cronin et al. 2015, Feeney, Stanhope et al. 2016, Jiménez-Reyes, Samozino et al. 2017). Importantly, there are important differences in how we conceptualize reliability. The term reliability can refer to a variety of different forms of reliability; nevertheless, in the context of performance assessment, it is the test-retest reliability that is of the greatest importance (Hopkins 2000). And especially between-day, test-retest reliability. The reason is that when we assess the performance of athletes, we are usually interested in changes in performance over time. Hence, how much the values we get vary from day to day is of great importance (Hopkins 2000). Similarly, for scientists, the case is the same when we measure the performance, for example, before and after a training intervention. Additionally, the term validity, which refers to the degree the method measures what it is supposed to measure, is also of great importance. The term agreement in this context is also used when we have multiple measurement methods and are interested in how accurately they compare to each other (Hopkins 2000). The main difference is that when we use the term agreement instead of validity, we do not necessarily compare it against the "gold standard". For example, if we wanted to compare the use of accelerometers and transducers to measure force, we would measure the agreement between the two and not validity, as both do not measure force directly. However, if we compared the accelerometer to the force plate, the term validity is then more commonly used as force-plate is a direct measure of force. When measuring force-velocity profiles, both agreement and validity are of great importance. Especially when there exists a multitude of methods, a systematic comparison across all methods (i.e., agreement) is of great interest. It is crucial to ensure that the measurement tool is accurate and consistent, as inaccurate results can lead to improper performance assessments. Therefore, it is essential to establish both reliability and agreement when measuring FV profiles in athletes. See Table 1 for an overview of studies on the topic.

Table 1: Overview of Studies on the reliability of various methods for measuring force-velocity profiles.

						Coefficient of variation (CV%)				
Study:	**Population:**	**Design:**	**Modality**	**Equipment**	**Loading:**	**F_0**	**P_{MAX}**	**V_0**	**S_{FV}**	**Conclusion**
Cuk et al. 2014	n=10 physically active males (23.4±3.0y, 77.3±8.0 kg, 182.6±4.2 cm).	4 sessions separated by a rest period of 5–7 day	Squat Jump (SJ) & Countermovement Jump (CMJ)	Forceplate	7 Loads from –30% to +30% BM (using a Pulley device)	SJ: 5.1 CMJ: 2.7	SJ: 5.4 CMJ: 2.2	SJ: 6.0 CMJ: 3.3	SJ: 9.8 CMJ: 5.7	«suggest that the obtained F–V relationships of leg extensors could be exceptionally strong, fairly linear, **highly reliable**, and of a moderate-to-high validity»
Giroux et al. 2015	n=17 sedentary & athletic individuals (23.7±3.7 y, 70.2±11.5kg, 171.9±8.6cm)	2 sessions separated by 1 week. (+ familiarisation)	Squat Jumps (in a squat rack)	Acceleromater, Linear Position Transducer, Foreceplate, Flight Time calculation	7 loads (0, 10, 20, 30, 40, 50 and 60% of 1RM).	No extrapolation to FV-profile. Mean CV% across loads and methods for force: 4.0% Velocity: 8.3%				«while all methods are **reliable**, the Samozino's procedure provides the greatest reliability»
Meylan et al. 2015	n=36 young students (13.1±1.1y, 49.5±11 kg, 160±10cm)	3 sessions seperated by 7 days	Supine squat machine	Linear Position transducer	5 load. 80%, 100%, 120%, 140%, and 160% body mass	7.6	8.5	13.8	24.2	«both the power –load and power – velocity relationships can be calculated relatively quickly and **reliably»**

Feeney et al. 2016	n=10 physically active males (21.9±3.2y, 72.2±5.4kg, 178 ± 12 cm).	2 sessions separated by 2 or 3 days of rest	Countermovement Jump (CMJ)	Forceplate	9 loading conditions (from 0–40% BM)	9.96	8.4	17.28	30.23	"an average **high reliability** and moderate concurrent validity of the obtained parameters"
García-Ramos et al 2017	n=23 collegiate men (23.1±3.2y, 74.7±7.3 kg, 177.1±7.0 cm)	2 sessions within 1 week.	Countermovement Jump (CMJ)	Forceplate & Linear Velocity Transducer	5 load. 17, 30, 45, 60, and 75 kg (barbell with & without smith machine)	No extrapolation to FV-profile. Mean CV% across loads and methods for force: 2.9% Velocity: 3.1%				"both jump types and both measurement methods could be **generally acceptable** for routine testing"
Jimenez-Reyes et al 2017	n=16 High-level male sprinters and jumpers (23.1±4.1 y, 76.3±6.4 kg, 181 ± 6 cm)	1 session (cross-sectional)	Countermovement Jump (CMJ)	Forceplate & Flight time calculation	6 loads ranging from BM to 87 kg	No extrapolation to FV-profile. Mean CV% across loads and methods for force: 0.3% Velocity: 0.4%				"all variables computed from the simple method showed **high reliability**"

Garcia-Ramos 2018	n=18 physical active men (22.3±2.1y, 75.7±7.0 kg, 177.7±6.3 cm)	4 sessions separated by at least 48 hours	Squat Jump (SJ) & Countermovement Jump (CMJ)	Forceplate	5 loads. 0, 17, 30, 45, 60, 75 kg. (comparing multiple & two load method)	All: 3-82%	All: 2-75%	All: 5-103%	All: 8-173%	"The two-point method based on distant loads is a **reliable** and valid procedure"
Janicijevic et al 2019	n=12, male sports science students (22.7±2.8 y, 79.6±8.7 kg, 1.82±0.08 m)	2 sessions separated by at least 48 hours	Squat Jump (SJ), preferred & 90 deg knee angle	Forceplate (FP) & Flight time calculation (SAM)	3 loads from BM to 61±12 kg	All: 2-6%	All: 3-4%	All: 6-10%	All: 8-15%	"The SAM procedure provided a comparable (SJ90) or higher (SJpref) reliability than the FP procedure"

Table 1 summarizes the studies assessing the reliability of various methods used to measure force-velocity profiles. The table details each study's population, design, modality, equipment, loading protocols, and the coefficient of variation (CV%) for Theoretical maximal force (F_0), velocity (V_0), power (P_{MAX}), and the slope of the FV-profile (S_{FV}). The conclusions drawn from each study are also given, providing insights into the reliability of different force-velocity profiling methods.

When it comes to common equipment to measure force and velocity (Table 2), Giroux et al. previously investigated the reliability and agreement among force plates, accelerometry, linear position transducers, and a flight-time calculation method during squat jump (Giroux, Rabita et al. 2015). They concluded that all three methods were reliable and in agreement. Consequently, they recommended that the methods can be used with confidence to measure the force-velocity profile. They included both sedentary and elite athletes in their study, which is a strength in this context. However, the study did not actually assess the Force-Velocity Profiles (as commonly expressed by: F_0, V_0, P_{MAX}, and S_{FV}) of the subjects. They only assessed the average force and average velocity from single repetitions that are used to extrapolate the profile. Although this might seem like a small detail, there are reasons to believe it makes a meaningful difference. A couple of years later, a study by García-Ramos et al. also investigated the same measurement methods, force-plate, transducer, and flight-time calculation method (García-Ramos, Pérez-Castilla et al. 2019). Like the study by Giroux, they found the individual force and velocity values to agree with each other across the methods. However, interestingly, when they extrapolated these values to create the FV-profiles, the differences were larger. Consequently, they cautioned against the use of linear transduces, and recommended to be cautious when measuring jump height which is used in the flight time calculation method. Nevertheless, they only investigated agreement across the methods, and not the test-retest reliability.

Table 2: Overview of Studies on agreement across methods for measuring force-velocity profiles.

						Correlation Coefficient				
Study:	**Population:**	**Design:**	**Modality**	**Equipment**	**Loading:**	**F_0**	**P_{MAX}**	**V_0**	**S_{FV}**	**Conclusion**
Giroux et al. 2015	n=17 sedentary & athletic individuals (23.7±3.7 y, 70.2±11.5kg, 171.9±8.6cm)	2 sessions separated by 1 week. (+ familiarization)	Squat Jumps (in a squat rack)	Accelerometer, Linear Position Transducer, Force plate, Flight Time calculation	7 loads (0, 10, 20, 30, 40, 50 and 60% of 1RM).	No extrapolation to FV-profile. Mean correlation across methods for force: 0.98 Velocity: 0.89				"In conclusion, the 3 present methods are similarly **valid** for assessing mean mechanical parameters"
Jimenez-Reyes et al 2017	n=16 High-level male sprinters and jumpers (23.1±4.1 y, 76.3±6.4 kg, 181 ± 6 cm)	1 session (cross-sectional)	Countermovement Jump (CMJ)	Force plate & Flight time calculation	6 loads ranging from BM to 87 kg	0.989	0.989	0.991	0.985	"allows **accurate assessment** of lower-limb force, velocity, and power properties"
Padulo et al 2017	n=10 male athletes (28.4±6.6 y, 77.4 ± 14.8 kg, 179 ± 8 cm)	3 sessions (cross-over), first = familiarization	Squat & Leg press	Force plate & Linear Velocity Transducer	~8 loads until 1RM was reached	Correlation not calculated. Effect sizes comparing squat and leg press ~1.8 - 3.2				"Lower-limb extensors mechanical capabilities **were different** in squat compared with leg press movements"
Garcia-Ramos et al 2019	n=13 Male judo Athletes (23.1±3.2 y; 74.7±7.3 kg; 177.1±7.0 cm)	1 session (cross-sectional)	Countermovement Jump (CMJ)	Force plate, Linear Velocity Transducer & Flight time calculation	5 loads from 0, 20, 40, 60 and 80 kg	~0.60	~0.79	~0.42	~0.27	"**large differences** were observed in the magnitude of mechanical output obtained"

Table 2 provides a summary of studies investigating the agreement across methods for measuring force-velocity profiles. Each row outlines a study's details, including population, design, modality, equipment used, loading parameters, correlation coefficients, and main conclusions. Abbreviations: Theoretical maximal force (F_0), velocity (V_0), power (P_{MAX}), and the slope of the FV-profile (S_{FV})

The V_0 and S_{FV} variables have shown substantially worse reliability than the other parts of the FV-profile when obtained in vertical jumping (Cuk, Markovic et al. 2014, Feeney, Stanhope et al. 2016, Janicijevic, Knezevic et al. 2019). Given that all measurements are taken closer to F_0 than V_0 and given the limited range in loads assessed during incremental loading protocols in vertical jumping, Cuk et al. theorized that this reduced reliability might be attributable to the distance of extrapolation (Cuk, Markovic et al. 2014). Garca-Ramos et al. observed that the reliability of V_0 is greatly affected by the load range utilized to acquire the FV-profile, lending credence to these hypotheses (García-Ramos, Pérez-Castilla et al. 2018). The technical difficulty of jumping with heavy loads limits the assessment of loads near F_0, while the subject's own body mass during vertical jumping limits attempts closer to V_0. On the other hand, during a leg press, body mass is not an issue, therefore it is possible to evaluate loads that are closer to both F_0 and V_0, which may increase the reliability of the FV-variables. Consequently, it is of interest to investigate whether the leg press task might show greater reliability for the FV-profile compared to vertical jumping.

Due to the critical importance of the test-retest reliability of the various approaches for assessing individual FV profiles, it is of considerable interest to study the gaps in the literature. Specifically, by investigating the test-retest reliability as well as agreement across commonly used measurement methods to assess force-velocity profiles in athletes.

1.5 Individualized Training Prescriptions

In practice, it is of great relevance to know the answer to the question of what athletes should prioritize in their training to get the greatest improvements in jumping performance. In the paper “Optimal Force–Velocity Profile in Ballistic Movements—Altius: Citius or Fortius?” Samozino et al.(Samozino, Di Prampero et al. 2012) explored this question using force-velocity (FV) profiling. To obtain an FV profile, an athlete performs maximal efforts against different loads during vertical jumping while force and velocity are measured. A linear regression is fitted to the force and velocity data, and then this slope is interpreted as the athlete’s individual FV profile.

Using a combination of experimental and simulated data, Samozino proposed the concept of a theoretical optimal FV profile (Samozino, Edouard et al. 2014). Briefly, the concept states that different athletes with similar theoretical maximal power (P_{MAX}) capacities vary in their jump height due to differences in the force-velocity profile. An athlete that produces his theoretical maximal power at a load greater than his body mass is categorized with a “velocity-deficit” (characterized as ‘velocity deficient’), whereas an athlete that produces his theoretical maximal power at a load lighter than body mass is categorized with a “force deficit” (as ‘force deficient’)(See example in Figure 4). The magnitude of the “deficit” of an FV profile is termed FV-imbalance (FV_{IMB}) and is the difference between the individual “optimal” FV profile and the observed profile. The individual optimal profile is based on reaching the theoretical maximal power at the athlete’s body weight. Subsequently, Samozino et al. suggest that athletes with a “velocity deficit” should prioritize “velocity-oriented” exercises in their training, whereas athletes with “force deficit” should prioritize “force-oriented” exercises in their training (Samozino, Edouard et al. 2014, Jiménez-Reyes, Samozino et al. 2017).

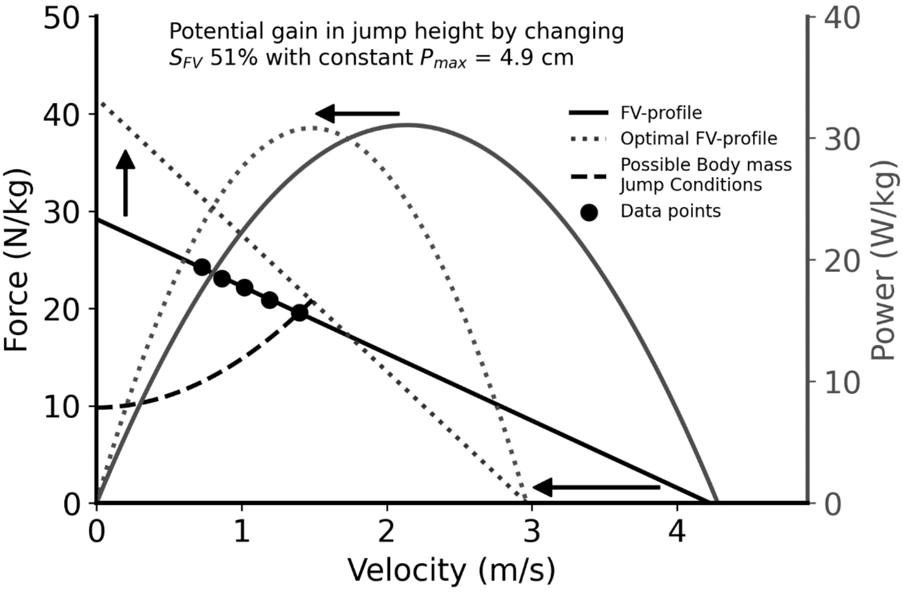

Figure 4. *Illustrating the concept of shifting the measured Force-Velocity (FV) profile towards a theoretically calculated optimal profile. In this example, shifting the measured profile to the optimal profile would result in a 4.9cm increase in jump height at the Body Mass (BM) load without changing the apex of the power curve (P_{MAX}).*

To test the proposed framework, Jiménez-Reyes et al. conducted an experimental study to test the hypothesis that training targeted to reduce athletes' FV_{IMB} is more effective than traditional resistance training irrespective of FV-profiles (Jiménez-Reyes, Samozino et al. 2017). The study supported the hypothesis, and the investigators concluded: "reducing FV_{IMB} without even increasing P_{max} leads to clearly beneficial jump performance changes". Accordingly, they stated: "FV_{IMB} could be considered as a potentially useful variable for prescribing optimal resistance training to improve ballistic performance". Following the initial experimental study in 2017, several other studies have investigated the topic. See Table 3 for a brief overview of the studies.

Table 3: Overview of Studies on the effectiveness of individualized training based on force-velocity profiling.

Author (year)	**Subjects**		**Training status**	**Individualization**	**Intervention Length**	**Intervention Type**	**Control Group**	**Results**	**Conclusion**
Jiménez-Reyes 2017	n=84 (23.1±4.4 y = 75.5±8.5 kg, 179 ±4.6 cm)	semi-professional soccer and rugby players	SJ =31±4 cm	Squat Jump - Theoretical Optimal FV-profile	9-weeks	2 day pr week Individualized strength and power training	2 day pr week general strength and power training	Changes in Jump height: Intervention: +11.3% Control: - 1.43% **Significan difference	"individualized training program specifically addressing the force-velocity imbalance is **more efficient** at improving jumping performance than a traditional resistance training"
Rakovic 2018	n=17 (23±3 y, 73 ± 6 kg, 177 ± 7 cm)	elite female handball players	30m time: 4.39s	Sprinting - Horizontal FV-profile	8-weeks	2 day pr week Individualized Sprint training	sprinting under normal conditions, no assistance or resistance	Changes in sprint time: Intervention: - 1% Control: -1% No difference	"An individualised sprint training program, …. **no more effective** than a generalised sprint-training program in improving accelerated and maximal velocity sprinting performance"

Jiménez-Reyes 2019	n=60 (23.7±3.7 y, 76.4±9.3 kg, 179 ± 00.5 cm)	professional futsal or semi-professional soccer and rugby players	SJ = 32±3 cm	Squat Jump FV-profile	9-24 weeks (12.6 ± 4.6)	2 day pr week Individualized strength and power training	No Control Group	Changes in Jump height: Intervention: +11.3% **<u>Significant increase</u>	"Individualized training program specifically addressing the force-velocity imbalance is **efficient** at improving jumping performance even in trained subjects."
Álvarez 2019	n=46 (18.9±1.1 y, 54.8±6.1 kg, 163.7±8.4 cm)	female ballet dancers	CMJ = 28±2 cm	Squat Jump FV-profile	9-weeks	2 day pr week Individualized strength and power training	No resistance training	Changes in Jump height: Intervention: +14% Control: -1% **<u>Significan difference</u>	A training plan addressing F-VIMB is an **effective** way of improving CMJ performance in female ballet dancers
Zabaloy 2020	n=34 (22±3 88±7 177±13)	highly trained rugby players	SJ = 30±4 cm	Squat Jump FV-profile	7-weeks	2 day pr week Individualized strength and power training	No Control Group	Changes in Jump height: Intervention: 0% <u>No Change</u>	"**no positive changes** were observed in jump performance for any of the interven tion groups"

Simpson 2021	n=29 (24±3 y, 94.9±21.6 kg, 181.3±6.0 cm)	highly trained rugby players	SJ = 40±7 cm	Squat Jump FV-profile	8-weeks	3 day pr week Individualized strength and power training	3 day pr week general strength and power training	Changes in Jump height: Intervention: +7% Control: 2% **Significan difference	"programming based …. F-V profile is a **more effective** method for improving F-V deficiencies, maximal strength, SJ, and peak-power"

Table 3 summarizes studies investigating the effectiveness of individualized training based on force-velocity profiling. Information is provided for each study's authors, subjects, training status, individualization measures, length and type of intervention, control group, key results, and conclusions.

Despite the substantial gains in jump performance previously reported after FV_{IMB}-individualized training, some questions remain unanswered (Jiménez-Reyes, Samozino et al. 2017, Álvarez, García et al. 2019, Jiménez-Reyes, Samozino et al. 2019, Simpson, Waldron et al. 2020). Multiple studies have demonstrated that muscular power strongly predicts explosive athletic ability (Sleivert and Taingahue 2004, Harris, Cronin et al. 2008, Morris, Weber et al. 2020). It is uncertain if a reduction in the squat jump (SJ)-FV_{IMB} without changes in P_{MAX} would be beneficial for other performance measures, such as the countermovement jump and sprinting performance. A change in the FV-profile without a corresponding increase in P_{MAX} indicates a decrease in power at high or low velocities (Jiménez-Reyes, Samozino et al. 2017). Such a change in the FV-profile could potentially be problematic if multiple performance goals are present or if the desired outcome involves a complex motor task that requires power production at both high and low velocities, such as sprint running. It is, therefore, of interest to explore the effectiveness of such individualized training on several performance outcomes that are typically tested and of relevance to coaches, such as CMJ height, maximal strength, 10, 30 m sprint, and power measures in movements other than the SJ.

In addition, based on the research on responders and non-responders, it is possible to hypothesize that individuals with a particularly developed capacity (i.e., being force or velocity oriented) possess this attribute because they respond effectively to this style of training (Mangine, Gonzalez et al. 2018). Therefore, it is crucial to consider whether some athletes should concentrate their training on their strengths rather than their limitations (i.e., opposite to the FV_{IMB} minimization approach). Furthermore, not all past research has found individualized training based on FV-profiling to be helpful, and some have questioned the measurement accuracy of the methodologies employed to produce FV-profiles. (Rakovic, Paulsen et al. 2018, Šarabon, Kozinc et al. 2021, Valenzuela, Sánchez-Martínez et al. 2021).

As can be seen in Table 3, there is a scarcity of studies investigating the topic, in addition to zero placebo-controlled studies. As a result of recent breakthroughs in placebo research, various types of interventions have, in fact, been questioned due to the likelihood of powerful placebo effects being present (McQuay and Moore 2005). Consequently, it is possible that earlier research findings were potentially influenced by placebos (Beedie, Benedetti et al. 2018). Due to obvious considerations such as blinding, most training interventions are unable to deliver placebos (i.e., we cannot tell subjects that they are lifting weights three days a week if they are indeed lifting six days a week) (Beedie and Foad 2009, Beedie, Benedetti et al. 2018, Hurst, Schipof-Godart et al. 2020). However, in the case of individualized training based on the FV-profile, the performance test that decides which style of training is "optimal" is a "black box" for the participants, making it an ideal setting to study the placebo effect. (i.e., participants can easily be randomized and told they get optimal or control training without knowing which is actually "optimal") (Jiménez-Reyes, Samozino et al. 2017, Rakovic, Paulsen et al. 2018, Álvarez, García et al. 2019, Jiménez-Reyes, Samozino et al. 2019, Simpson, Waldron et al. 2020, Zabaloy, Pareja-Blanco et al. 2020). Consequently, in practice, two people may be performing the exact identical workouts, but it may be "optimal" for one and "sub-optimal" for the other.

We know very little about the possible placebo effect at this time when examining various training combinations (e.g., exercise selection, loading, volume, frequency). Therefore, the purpose of the current study was to determine whether there is a placebo effect when participants are informed; they get "optimal training" as opposed to being informed they are receiving general "control training."

It is thus of the utmost relevance to investigate the aforementioned unknown aspects that are associated with the FV-training methodology.

2 Aims

The overarching aim of this Ph.D. dissertation was to investigate the use of force-velocity profiling for performance assessment and individualized training prescriptions in Athletes. Three experimental studies were conducted to this end. These studies addressed three specific aims:

The aims of these projects were to:

1. Assess the reliability and agreement across commonly used measurement equipment for assessing force-velocity profiles in well-trained and elite athletes. (Study I)
2. Investigate the effectiveness of an individualized training approach based on FV-profiling on jumping in well-trained athletes. (Study II)
3. Investigate whether a placebo effect is present when participants are told they get "optimal training" compared to being told they get generic "control training. (Study III)

We hypothesized that:

- The FV-variables (F_0, V_0, P_{max}, S_{FV}) obtained from different measurement equipment would show inconsistencies and lack agreement across the equipment. The reliability would depend on the equipment and procedures used.
- An individualized training approach would increase jump height significantly more than a traditional power training regimen.
- A placebo effect would be observed when participants were told they were receiving “optimal training” as opposed to being told they were participating in “control training”.

3 Methods

Data from three experiments are presented in this thesis. The data collection from study I was performed over a longer period from 2016 to 2019; the data from study II were collected in 2019, and study III in 2021. The data was gathered from various regional Olympic testing and training facilities in all three studies.

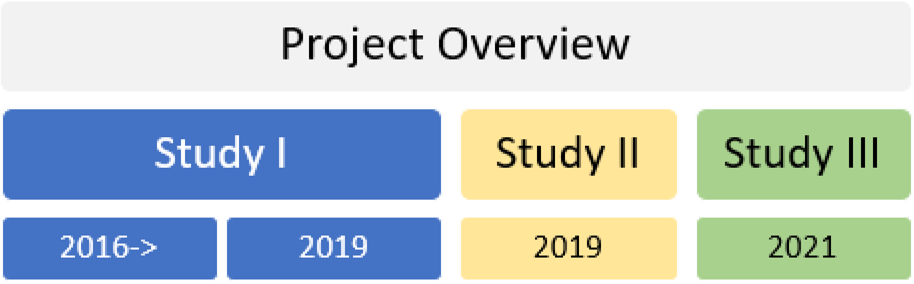

Figure 5. *Project timeline overview of the three studies included in this thesis.*

3.1 Participants

In total, 216 participants were initially included for testing across all three studies (Table 4). Prior to their participation, all individuals provided written informed consent and received an explanation of the study's nature and objectives.

In ***study I***, sample sizes varied between measurement methods due to variable facility testing capacities. Thus, the main analysis in this study was on participants assessed under all methods (reliability and agreement), with an extra aggregated analysis encompassing all participants, with varied sample sizes across methods (only reliability analysis) (See flow chart in Figure 6). A total of 27 well-trained male handball and ice hockey athletes were included in the main analysis (age 21±5 years; height 185±8 cm; body mass 84±13 kg). Both male (~80% of the sample) and female athletes were included in the mixed sample (age 21±4 years; height 182±9 cm; body mass 78±12 kg). Most athletes competed in handball, ice hockey, soccer, and volleyball as teams, while the remaining competed in speed skating, badminton, weightlifting, Nordic combined, ski jumping, and athletics. The majority competed at the national and international levels in their respective sports, ranging from world-class (Olympic medalist) to club level (See Table 4).

For ***study II***, a total of 46 athletes were recruited, where 40 male athletes completed all testing sessions (age 20 ± 4 years; height 184 ± 9 cm; and body mass 83 ± 13 kg). The participants were handball (n = 14), ice-hockey (n = 16), and soccer (n = 10) national-level team sport competitors. The handball and ice-hockey players were elite-level athletes, while the soccer players were club-level athletes. (See Table 4).

In ***Study III***, a total of 71 athletes were recruited; however, due to the COVID-19 pandemic, some participants became sick or quarantined and were unable to finish the intervention or assessment sessions (See flow chart in Figure 8). A total of 40 male and female athletes (age: 22±4 years, height: 183±10 cm, and body mass: 84±15 kg) completed the study. The athletes played handball (31 males) and soccer (nine females) at national and club levels, respectively.

Table 4: Participant overview

	*N=**	*Age (y)*	*Body mass (kg)*	*Training Status*
Study I	100 (57)	21 ± 4	78 ± 12	World class (Olympic medalist) to club level
Study II	46 (40)	20 ± 4	83 ± 13	National level team sport players
Study III	70 (40)	22 ± 4	84 ± 15	National level team sport players

**Numbers in parentheses = subject completing pre and post testing. Y: Years, kg: Kilograms*

3.2 Experimental design

The participants in ***Study I*** were assessed on four distinct occasions. The first two testing intervals were separated by approximately one week, followed by a period that lasted between two and six months. Similarly, the last two testing timepoints were again separated by approximately one week (Figure 6).

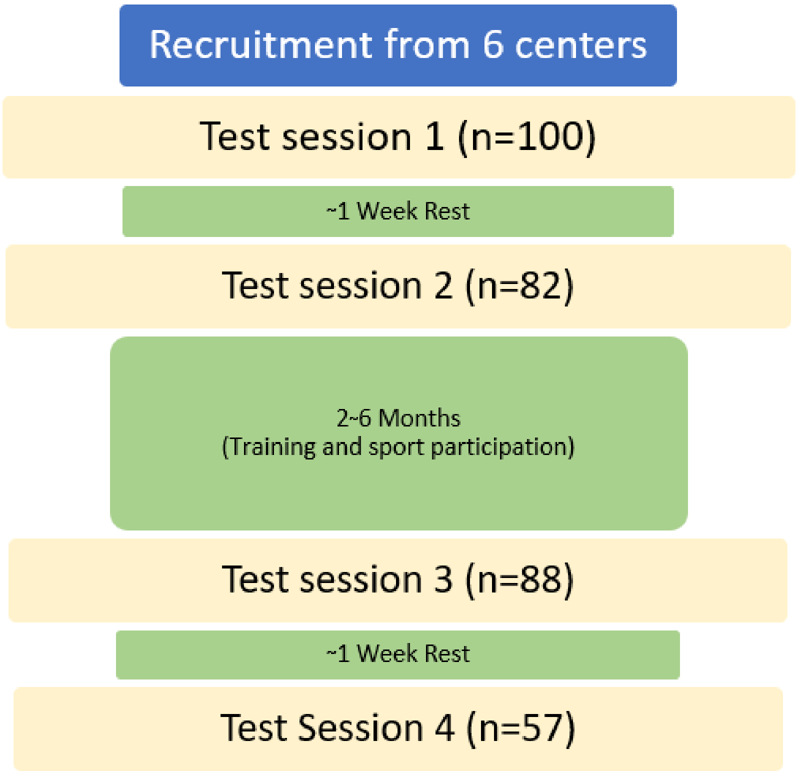

Figure 6. *Flow chart illustrating the timeline and number of participants (n) completing the various testing-timepoints in study I.*

The data was collected from several Olympic training and testing facilities situated in various areas. Because the testing capability of the various facilities varied, the sample size for each measurement technique was distinct. Consequently, the primary analysis in this study was conducted on the individuals who were subjected to all techniques (reliability and agreement), in addition to an aggregated analysis that included every single participant. The test leaders were consistently the same for the primary analysis. However, for the aggregated study, test administrators and equipment differed among locations, although being the same for each participant (sample sizes for all tests are presented in the results section).

For Study II, each participant was first familiarized with the testing procedures, followed by a pre-test, ten weeks of training, and a post-test. The pre-test was administered around one week before the first training session, while the post-test was administered roughly one week after the end of training. Both pre-test and post-test testing sessions were conducted at around the same time of day (±2 hours). According to previously proposed methods, each athlete completed an incremental loading procedure in the SJ to identify their individual FV-profile as well as their theoretical optimal profile. The difference between the measured and the calculated FV-profile results in the “Force-Velocity Imbalance” (FV_{IMB}), which was used to randomize the athletes to the different training groups.

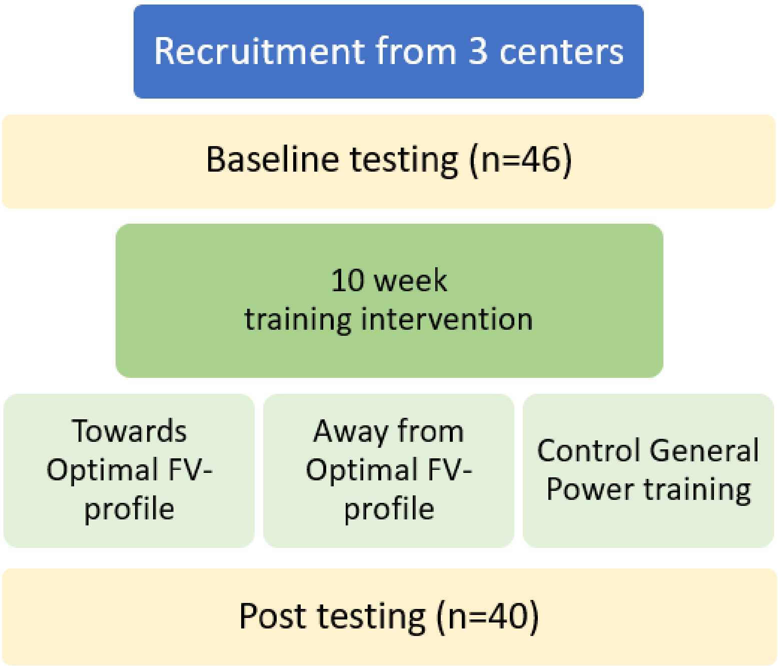

***Figure** 7. Flow chart illustrating the timeline and number of participants (n) completing the various testing-timepoints in study II.*

Participants were assigned to the various training groups using stratified randomization depending on their FV_{IMB} at baseline. Specifically, after sorting the individuals from biggest to lowest FV_{IMB}, each third pair was randomly assigned to perform either heavy strength training, high-velocity strength training, or a combination of the two (See Table 5 for a summary of the training programs).

The threshold for FV deficits was established based on the FV-profile in percent of optimal: 110 percent for force deficits, 90 for velocity deficits, and 90 percent to 110 percent was deemed well-balanced. So, the participants who were randomly allocated to reduce their FV_{IMB} (i.e., those with a force deficit who trained heavy strength, those with a velocity deficit who trained high-velocity strength, and those with a well-balanced profile who trained a mix of the two) were the ones that trained toward their optimal profile. The participants who were randomly assigned to train to increase their FV_{IMB} (i.e., force deficit participants training high-velocity strength, velocity deficit participants training heavy strength, and well-balanced participants training either high velocity or heavy strength) were training away from their optimal profile. The non-optimized balanced training group was comprised of individuals who were randomly assigned to balanced heavy and velocity training and had either a force or velocity deficit at baseline. This allocation resulted in the three groups training toward, away from, or regardless of their initial theoretically ideal FV-profile.

The participants in Study III initially performed baseline tests, then a 10-week training intervention, and finally, post-intervention tests. The participants were first randomized to one of two groups: Placebo or Control. In each of these groups, subjects were again randomly assigned to either a general power training program or a personalized training program based on their force-velocity profile. The research design is depicted in Figure 8.

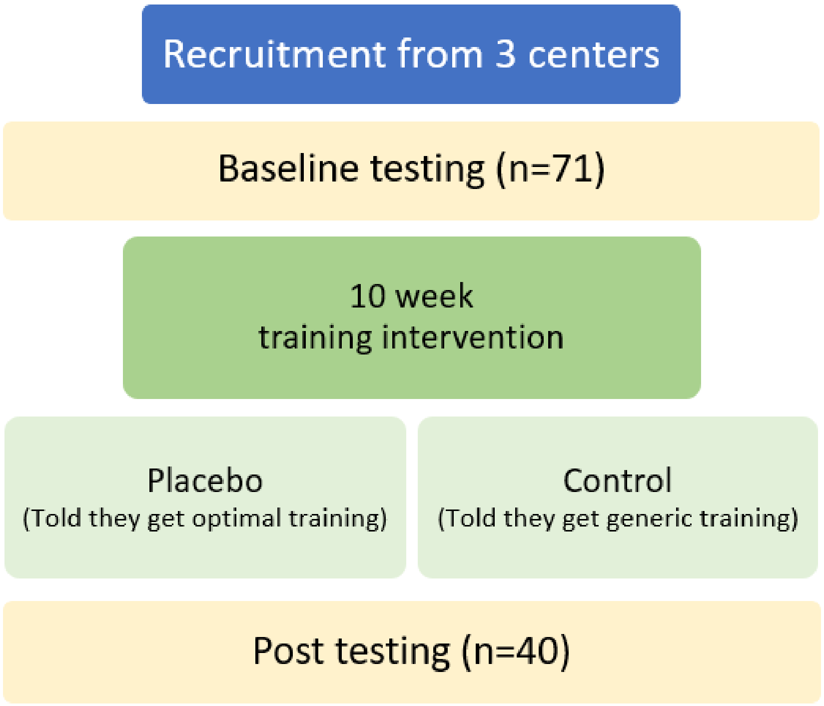

Figure 8. *Flow chart illustrating the timeline and number of participants (n) completing the various testing-timepoints in study III.*

To deliver the placebo “treatment”, the participants were either informed that the training program they received was customized based on their force-velocity profile or that they were in the control group. This implies that individuals in both groups performed comparable workouts, but half of them thought they were receiving ideal individualized training (Placebo), and the other half believed they were receiving suboptimal generic training (Control) (Figure 8). Importantly, because the baseline FV profiles were produced by a researcher who did not take part in the testing or training of the athletes, the FV profile was unknown to the participants and researchers participating in the testing and training. As a result, delivery of the placebo was made possible by informing a subset of patients that their profile differs from that which was assessed. For instance, individuals in the Placebo group who received "force-focused training" were informed that their FV profiles were velocity-based (force "deficient") and that heavy load training was the best training for them. In contrast, members of the Control group received no information on their FV profiles. They were informed that they were part of the control group and that the training program they got was designed to enhance performance without individualization based on FV-profiles. These instructions were communicated orally and in writing to all participants.

Each program included written information regarding which group each athlete was allocated to., i.e., Individualized or control training, together with the following information:

> *«The program is based on research that shows that it is beneficial to train on the characteristic you are "bad" at. For example, if you performed worst on heavy weights, the program include more heavy training. Conversely, if you were worst at light weights, the program will contain mostly light weights.*
>
> *As this training is part of research, half of the participants are randomly divided into a control group, who receive training regardless of what they are good or bad at. All the training programs will have a beneficial effect, but there is still uncertainty about which is best.»*

3.3 Ethical Considerations

Study I was assessed by the Inland Norway University of Applied Sciences' ethical committee, and Study II and II was assessed by the ethical board of the faculty of sport science and physical education at the University of Agder. All three were authorized by the Norwegian Centre for Research Data and conducted in accordance with the Declaration of Helsinki. The people who took part in the study had to be healthy and not on any drugs that could affect the results. In addition, all subjects participating in the studies provided written informed consent.

For Study III, the participants in both the placebo and control group were correctly informed that the training programs would be beneficial; where the only difference was that there was a greater emphasis on the positive benefits of the placebo/individualized training. It is possible that greater emphasis on, for example, negative effects from the control group would induce a nocebo effect, i.e., a negative effect out of negative expectations. However, we did not deem such an experiment ethical, as it could potentially harm the athletic development of the athletes. Importantly, in regard to the way we chose to run the experiment, by only inducing positive expectations, we deemed that ethical, as no harm would be caused to the athletes.

3.4 Training protocols

For Study I, there was no structured training included in the study design. In the period between the double reliability testing sessions, the athlete continued their regular athletic development and competition schedules. This did not interfere with the purpose of the experiment, as we were not looking at what happened in the period between the double reliability sessions.

The training protocol in Study II consisted of two sessions per week for ten weeks. The minimum time between sessions was 48 hours. The training approach was based on previous research on FV_{IMB}-based individualized training (Jimenez-Reyes, Samozino et al. 2016). Most of the exercises in the force program were done with heavy weights, while the exercises in the velocity program were done with lighter weights and faster speeds. The balanced heavy and velocity program consisted of a combination of both heavy load hand high-velocity exercises. The training content of the different programs is summarized in Table 5 and is attached in their full form in the appendix. All exercises were performed at the maximal intended velocity. In addition, the research team oversaw the sessions to ensure appropriate implementation of the programs. The intensity of the heavy exercises was regulated by repetitions in reserve with rep ranges corresponding to relative intensities of 70 percent or greater of 1RM (Helms, Cronin et al. 2016). The workouts with lower weights and greater velocities comprised different jumping exercises with body mass, light loads, and rubber bands as unloading. During the sessions, the athletes received verbal input from the research assistants and coaches. In addition, for a chosen number of sessions (4–5), the athletes received objective feedback from linear transducers on certain explosive activities.

Table 5. Training content for the three different training programs

	Exercises	**Reps**	**Load**	**Weekly sets**	**Focus**	**% of sets**
Force program	Deadlift, Hip-thrust, Front squat, Squat, Stiff-leg dead lift, Bulgarian split squat, Trapbar Deadlift, Calf-raises	3-10	1-6 RIR	14	Strength	82 %
	Trapbar Deadlift	5	50-70% 1RM	4	Power	18 %
Balanced program	Deadlift, Front squat, Bulgarian split squat, Hip-thrust, Deadlift	3-10	1-6 RIR	13	Strength	46 %
	Box jumps, Stair jumps, Single leg stair jumps, Squat jump w/rubber band, Stair jumps, Trapbar jumps	5-10	Negative-50% 1RM	15	Power	54 %
Velocity program	Half Squat, Hip-thrust	3-8	1-2 RIR	6	Strength	21 %
	Squat jumps, Trapbar jumps, Step up, Squat jump w/rubber band, countermovement jumps, box jumps, Clean Pull, Stair jumps, Single leg stair jumps	5-10	Negative-50% 1RM	22	Power	79 %

RIR= Reps in reserve, 1RM=One repetition maximum, reps=repetitions, Set=training sets.

For Study III, the subjects performed the same workouts as study II (Table 5). However, the main difference was the group allocations, as described earlier, and the fucus on expectations towards the training intervention. Each subject got then a written note together with their program explaining which group they were allocated to, as well as a not in the top corner of the program (appendix VI). Oppositely to study II, the training sessions in study III were not supervised by the research team.

3.5 Testing Procedures

In all three studies, the athletes were instructed to prepare as they would for a regular competition in terms of what they eat, drink, and how much sleep they get and to avoid hard exercise 48 hours before testing. All tests were conducted indoors, and participants were advised to wear the same clothing and footwear on each test day. Prior to testing, all participants completed a normal 10-minute warm-up consisting of jogging, local muscle warm-up (consisting of light dynamic stretches for hamstring and hip mobility), running exercises (e.g., high knees, skipping, explosive lunges), and bodyweight jumps.

The testing protocol in Study I consisted of a series of squat jumps (SJ), countermovement jumps (CMJ), and a leg press test with increasingly higher resistance. In Study II, the testing protocol included a series of SJ, CMJ, 30-m sprints, 1RM back squat, and a leg-press test with increasing loads and in the mentioned order. The protocol for Study III includes a series of CMJs with progressively heavier weights, 20-meter sprints, 1RM back squats, and leg-press tests. All subjects were given verbal encouragement and instructions to assist them in performing their best on performance tests. In addition to the physical performance tests, in Study II and III, ultrasound measurements were taken prior to the physical tests or on a separate test day. In Study III, subjects also answered a questionnaire regarding expectations before and after the training intervention.

Using a brightness mode (B-mode) ultrasonography apparatus (Telemed ArtUS EXT-1H, IT, 70 Hz, Vilnius, Lithuania, EU) with a 60-mm probe (LV8-5N60-A2), the resting muscle thickness of the *m. rectus femoris* was measured.

All participants lay supine with their knees completely extended on an examination bench. Forty percent of the distance between the lateral epicondyle of the knee and the greater trochanter was determined. Each subject's ultrasound settings (Gain, frequency, and depth) were tuned and maintained during all test sessions in order to emphasize collagenous tissue that comprises muscular aponeuroses and surrounds muscle fascia. It was recorded on a translucent sheet in relation to natural features such as scars, moles, birthmarks, etc. All ultrasound images were blindly examined with ImageJ (version 1.46r, National Institutes of Health, USA). Ultrasound measurements were extracted from one image per individual. Based on pilot testing, we determined that this approach has a test-retest variance of 3%.

For the evaluation of expectation effects, a modified version of the Stanford Expectations of Treatment Scale (SETS) was used. The SETS scale is a previously validated instrument used to evaluate positive and negative treatment expectations in clinical studies (Younger, Gandhi et al. 2012). To make the questionnaire possible to give to the participants, it was translated into Norwegian, and a few items were omitted. All participant surveys were checked to see whether any were missing or incomplete. Responses that were left blank, patterned, or all marked with the same option were omitted from the analysis. Each participant was advised to keep track of each completed training session to ensure program adherence. The participant reported the number of completed sessions together with the SETS questionnaire at the post-test. In agreement with past studies, percentages of adherence were then given (i.e., percent completed sessions of scheduled sessions).

For study I and II, the following procedures were followed for the SJ and CMJ jumps. Both the SJs and CMJs were performed initially with bodyweight, followed by a progressive loading regimen of 0.1 (broomstick), 20, 40, 60, and 80 kg. For weaker individuals (those unable to jump with 80 kg), a procedure of around five loads, individually determined, up to 80 % of bodyweight was applied. In order to calculate the force-velocity (FV) relationship, both the squat jump and countermovement jump tests were performed using a force plate (main analysis in Study I and Study II was conducted using the Musclelab by Ergotest AS, Porsgrunn, Norway, while some athletes in the aggregated analysis were tested on the AMTI force plate, Advanced Mechanical Technology, Inc, Waltham Street, Watertown, USA). In study I, in addition to the force-plate, a linear position transducer encoder (by Ergotest AS, Porsgrunn, Norway) was mounted on the barbell and placed on the ground. To conduct the bodyweight trials, subjects were told to put their hands on their hips, and a broomstick was used to represent the 0.1 kg weight. Two valid tests were conducted for every load, and after each attempt, the subjects were given a rest interval of between one and three minutes. During the SJ, participants started with their knees bent at a 90-degree angle, held this position for 2 seconds, then quickly jumped as high as possible before landing with their ankles extended. To ensure proper form, participants were not allowed to perform a countermovement, and the direct force output from the force plate was used to visually check for this. The starting position for both the SJ and CMJ was standardized to the individual's self-selected starting position and kept constant for all jumps and testing sessions. The starting position for the SJ and the depth of the CMJ was monitored using a rubber band placed beneath the athletes' thighs. If these conditions were not satisfied, the trial would be repeated. The procedure for the CMJ was similar to the SJ, except for a pause in the bottom position. The CMJ was performed with the same precautions and requirements as the SJ to ensure the accuracy and consistency of results.

In study III, the CMJs were performed using an incremental loading protocol consisting of 3 different loads, starting with the athlete's bodyweight and increasing to 40kg. The final load was adjusted for each individual to aim for a jump height of approximately 10cm (ranging from 60 to 90kg). The subjects completed 2-3 jumps (x 2) for the bodyweight and 40kg conditions and 1-2 jumps (x2) for the heaviest load. The rest periods between jumps within a set were approximately 10-20 seconds, with a break of 2-3 minutes between sets and loads. To maintain consistency, the CMJ depth was standardized to the individual's self-selected starting position and monitored both visually and through the displacement output from the force plate software. The jump height was measured using a 1000 Hz force plate (either the AMTI Advanced Mechanical Technology, Inc. force plate located in Waltham Street, Watertown, USA, or the Kistler 9286B force plate from Kistler Instruments AG). The height was calculated from the impulse, and the average of the best two trials for each jump condition was used for further analysis.

In study II, 30m sprints were performed, and in study III, 20m sprints were performed. The participants completed 2 to 4 all-out sprints with a rest period of 3 to 5 minutes between each trial. The timing was initiated when the front foot left the ground and was measured at 5-meter intervals using wireless timing gates (from Musclelab, Ergotest Innovation AS). The best 30-meter (or 20m in study II) time from all the trials was selected for further analysis.

In studies II and III, The one repetition maximum (1RM) back squat was determined using a standard protocol, which involved progressively increasing the load until the individual's maximum weight was reached. Before attempting the 1RM, submaximal squats were performed with 2 to 4 repetitions at 50% and 60% of the 1RM. These were part of a warm-up, followed by one repetition each at 80%, 90%, and 95% of the 1RM (self-estimated at the first measurement). The participants then had 2 to 3 trials at the 1RM load, with a rest period of 2 to 3 minutes after each attempt. The smallest load increase was 2.5 kilograms, while the greatest load that was lifted successfully and at a standardized depth (with the top of the thigs at the hip joint below the knee) was recorded as the participant's 1RM.

A Keiser A300 horizontal leg-press dynamometer was utilized for the leg-press testing (Keiser Sport, Fresno, CA). The FV-profiles were extracted from a pre-programmed 10-repetition FV-test in the Keiser A420 software. Two practice reps with the lowest weight (~15 percent of 1RM) were performed before the actual test. Afterward, the load was steadily raised with fixed increments (20–30 kgf [kilogram-force]) for each repetition until achieving the 1RM load, for a total of ~10 tries throughout the FV-curve (15–100% of 1RM). As the load increased, the rest-time between tries increased. The rest time between tries was 10–20 seconds for the first five attempts and 20–40 seconds for the following attempts. In the main analysis in study-I and study-II, the 1RM load for each participant was acquired during the familiarization session. In the aggregated analysis in Study I and in study III, the 1RM load was subjectively determined by the test leaders. Subjectively determining the 1RM for the loading range sometimes results in either extra or fewer repetitions than the standard 10-reps. Each participant's sitting position was modified to achieve a vertical femur, corresponding to an 80-90 knee angle, and the feet were positioned with the heels at the bottom of the foot pedal. Participants were instructed to extend both legs with maximum effort during the 10-repetition FV test. As a result of the pneumatic semi-isotonic resistance, maximal effort does not result in ballistic action, and the full push-off was executed with maximum intended velocity. As the pedals rested in their predefined position prior to each repetition, the leg press was done as a concentric-only exercise without any eccentric movement. The submaximal eccentric phase was not recorded.

3.5 Data Analysis

To obtain the force velocity (FV) variables from the CMJs, SJs, and leg press tests, time-average force and velocity were computed from the movement's concentric phase. To get the individual FV variables (F_0, V_0, P_{MAX}, and S_{FV}), a linear regression was fitted to the measurements obtained from each incremental loading test. F_0 and V_0 represent the intercepts of the linear regression for the force and velocity axes, while S_{FV} refers to the slope of the linear regression. P_{MAX} was then calculated as F_0 x V_0 / 4, using FV profiles with a coefficient of determination greater than 0.95.

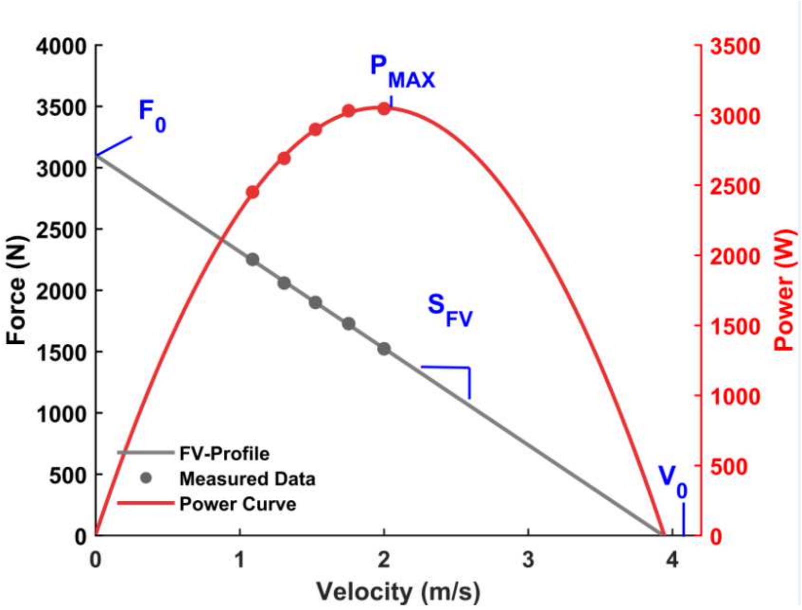

***Figure 9**. Example Force-Velocity Profiles from a Vertical Jumping task. Illustrating the used variables: Theoretical maximal force (F_0), velocity (V_0), power (P_{MAX}), and the slope of the FV-profile (S_{FV})*

The force plates measure ground reaction forces, and the velocity (v) is then calculated by integrating the acceleration (a) obtained from the ground reaction forces (F) in relation to the mass of the object (m) (Equation 2-3) (Halliday, Resnick et al. 2013). The center of mass position (x) was determined by integrating velocity (v) (equation 4), while power was calculated as the product of force and velocity (Halliday, Resnick et al. 2013).

Equation 2:

$$a = \frac{F}{m}$$

Equation 3:

$$v = \int a \, dt$$

Equation 4:

$$x = \int v \, dt$$

The start of the concentric phase for the squat jump (SJ) was defined as the point where force exceeded five standard deviations (SD) of the steady-stance weight prior to the jump, while for the countermovement jump (CMJ), it started when the force fell below 5 SD of the steady-stance weight. The concentric phase was defined as the point where velocity was greater than 0 m/s and ended when the participant left the force plate (when forces fell below 10 N). The measurement sample rate for the MuscleLab force plate was 200 Hz, then up-sampled to 1000 Hz utilizing the embedded software's spline integration, and the AMTI force plate was sampled at 2000 Hz.

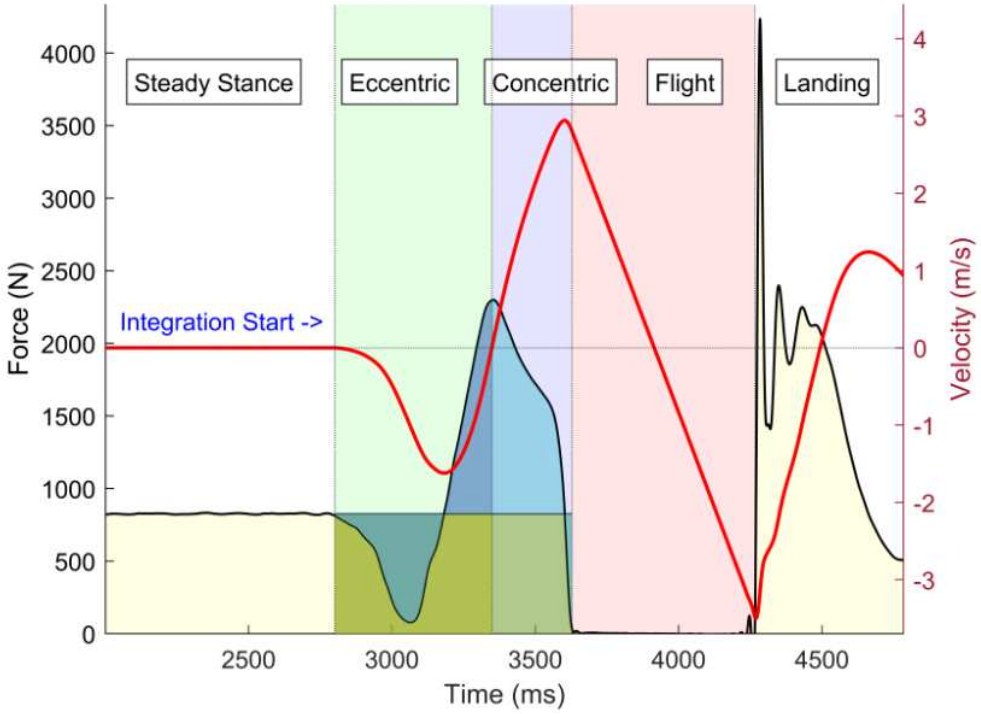

Figure 10. *Example Force-Time trace from a Vertical Jump. The left axis represents the ground reaction forces, whereas the right axis represents the calculated velocity of the center of mass.*

For the encoder, the software was used to calculate force and velocity by measuring the position of the cable (connected to the bar) as a function of time. The average force was calculated as the product of mass and acceleration, with mass calculated as body weight plus external load. The manufacturer's recommendation and previous studies were followed, using 90% of body mass and 100% of the external load to calculate force during SJ and CMJ. The measurement sample rate for the MuscleLab encoder was 200 Hz.

For the flight time method, jump heights were calculated based on the time the participants were in the air. Obtained from the force-time signal recorded by the force plates. The method of calculation involved using equation 5, where g is the acceleration due to gravity, t is the flight time, and h is the jump height (Halliday, Resnick et al. 2013).

Equation 5:

$$h = \frac{g \times t^2}{8}$$

Average force (*F*) and velocity (*V*) were calculated using two equations (Equation 6 - 7), considering the input variables mass (m), jump height (h), push-off distance (hpo), and the gravitational acceleration (g) (Samozino 2018).

Equation 6:

$$F = mg\left[\left(\frac{h}{hpo}\right) + 1\right]$$

Equation 7:

$$V = \sqrt{gh/2}$$

The gravitational acceleration was set to 9.81. The Vertical Push-Off distance was calculated as described in a previous study (Samozino 2018). This distance represents the difference in length between the lower limb in its extended position with maximum plantar flexion and the crouching beginning posture of the jump.

The leg press dynamometer measures compression forces and positional changes of the piston in the air cylinder. Velocity is calculated as the derivative of the position over time. To account for the fact that the leg extension phase is not identical to the change in the cylinder position, the in-built Keiser software recalculates the values at the cylinder to match those of the foot pedals (as described in the Keiser A420 manual). The average force and velocity were calculated as a function of time, excluding 5% of the range of motion from the start and end of the movement. The measurement sample rate for the leg press apparatus was 400 Hz.

The optimal FV-profile was calculated according to Samozino's method (Samozino, Di Prampero et al. 2012). The Force velocity Imbalance (FV_{IMB}) is a computed number representing the discrepancy between the actual and optimal FV profiles. An optimized FV profile is indicated by a value of 100 percent. Values greater than 100% indicate an imbalance in the individual's FV profile, where there is a deficit in velocity capabilities. On the other hand, if the value is less than 100%, it suggests an imbalance with a deficit in force capabilities. This difference between the actual FV profile and the optimal FV profile represents the magnitude of the imbalance, and the greater the deviation from 100%, the larger the imbalance (Equation 8).

Equation 8:

$$FV_{\mathrm{IMB}} = 100 \times \frac{SFV}{SFV_{\mathrm{OPT}}}$$

3.7 Statistical Analysis

In study I, to evaluate the reliability across testing sessions, we utilized three different measures: the coefficient of variation (CV%), the interclass correlation coefficient (ICC 3,1), and the mean percent change (%Δ). The CV% and %Δ were obtained from log-transformed data while utilizing the Pearson product-moment correlation coefficient (Pearson r) to investigate the relationship across methods. To compare the methods, we calculated the mean difference (systematic bias) in both absolute and relative terms, expressed as a percentage of log-transformed data. The standardized difference was then interpreted using a qualitative scale: <0.2 (Trivial), 0.2–0.6 (Small), 0.6–1.2 (Moderate), 1.2–2.0 (Large), 2.0–4.0 (Very Large), >4.0 (Extremely Large) (Hopkins 2000). A paired sample t-test was used to test the significance level of the difference in means, and a linear regression analysis was conducted to compare methods, including the calculation of the standard error of the estimate (SEE) and presentation in both absolute and relative terms.

For the comparison across methods, we analyzed the average of the two first testing timepoints. The smallest worthwhile change (SWC%) was calculated as 0.2 of the between-athlete standard deviation and was expressed as a percentage of the mean. The confidence limits for all analyses were set at 95%. The Pearson's r coefficients were interpreted according to a categorical scale defined by Hopkins and Marshall: <0.09 (Trivial), 0.10–0.29 (Small), 0.30–0.49 (Moderate), 0.50–0.69 (Large), 0.70–0.89 (Very Large), 0.90–0.99 (Nearly Perfect), 1.00 (Perfect). Acceptable reliability was considered as ICC > 0.80 and CV > 10%, while good reliability was determined as ICC > 0.90 and CV > 5% (Hopkins 2000). All data were reported as mean ± standard deviation. The statistical analyses were performed using a customized Microsoft Excel spreadsheet (Hopkins 2017).

Study II The sample size was determined using G*Power 3.1.9.2, with a desired power of 80% and an alpha of 5%. The minimum required sample size was calculated to be 34 participants, with a target effect size (Cohen's f) of 0.5. A one-way ANCOVA was used to examine between-group differences, with baseline measures as the covariate. Within-group pre-post changes were analyzed with a paired sample t-test, and Pearson's r was used to assess relationships between the FV-variables and performance measures. Multiple regression was performed to determine the contribution of P_{MAX} and FV_{IMB} to variance in SJ height.

The standardized effect size was calculated as pre-post change divided by the pooled pre-SD from all participants and categorized using the same scale as presented earlier in the chapter. Results are presented as mean ± SD, and confidence limits are set at 95% with a significance level of <0.05. All statistical analyses were performed using Microsoft Excel 2016 and IBM SPSS Inc. (version 25).

Study III In addition to traditional null-hypothesis testing, we used a Bayesian approach for the analysis as it is more robust in the case where the sample size for some of the measures may be smaller. The Bayesian approach is less dependent on sample size compared to traditional p-values. Before analysis, the data was checked for normal distribution using the Shapiro-Wilk test. An independent sample t-test was performed to examine the differences between the placebo and control groups for all the included measures, as well as to assess baseline differences between groups. The SETS variables were not found to have a normal distribution, so the median and quartiles were used to describe them. For the upper and lower quartiles, a rank-biserial coefficient of correlation was used to look at the differences between the groups. To control for potential confounding effects from expectancy measures and subject adherence, an ANCOVA was also conducted.

A paired sample t-test was used to examine changes within each group before and after the intervention. The standardized effect size (ES) was calculated by dividing pre-post changes by the pooled pre-SD from all participants and was categorized similar to the previously mentioned scale.

Means with the corresponding variance are presented with standard deviation (SD) unless otherwise stated. The interpretation of the Bayes factor (BF_{10}) was based on the scale proposed by Jeffreys, where 1-3 is considered anecdotal, 3-10 is substantial, 10-30 is strong, 30-100 is very strong, and >100 provides decisive evidence for H1. A $BF_{10} < 1$ suggests support for H0. The significance level was set at 0.05, and the confidence level was set at 95% for all analyses. The statistical analyses were conducted using JASP version 0.14.

4 Findings

4.1 Test-retest reliability of the FV-variables (Study I)

The reliability measures for the FV-variables are presented in Paper I in detail and also illustrated in Figure. 11 here. Out of all the measurement methods tested, only the leg press displayed acceptable reliability for the four FV-variables F_0, V_0, P_{MAX}, and S_{FV} (CV: 3.7–8.3%, ICC: 0.82–0.98). The CMJ and SJ displayed acceptable reliability measures for P_{MAX} and F_0 (CV: 3.9–12.1%, ICC: 0.61–0.97); however, the reliability measures for V_0 and S_{FV} were unacceptable for both the squat jump (SJ) and the countermovement jump (CMJ) measurement methods (CV: 8.4–30.1%, ICC: 0.16–0.79). The typical error for the jump height in both SJ and CMJ was 1.2 cm, corresponding to a CV of 6.8%. The typical error for each load condition (0, 20, 40, 60, and 80 kg) was 1.7, 1.2, 0.9, 1.0, and 1.0 cm, respectively, corresponding to CV values of 5.1, 4.6, 5.5, 7.6, and 10.2%. Individual R^2 values for each FV-profile ranged from 0.95 to 1.00.

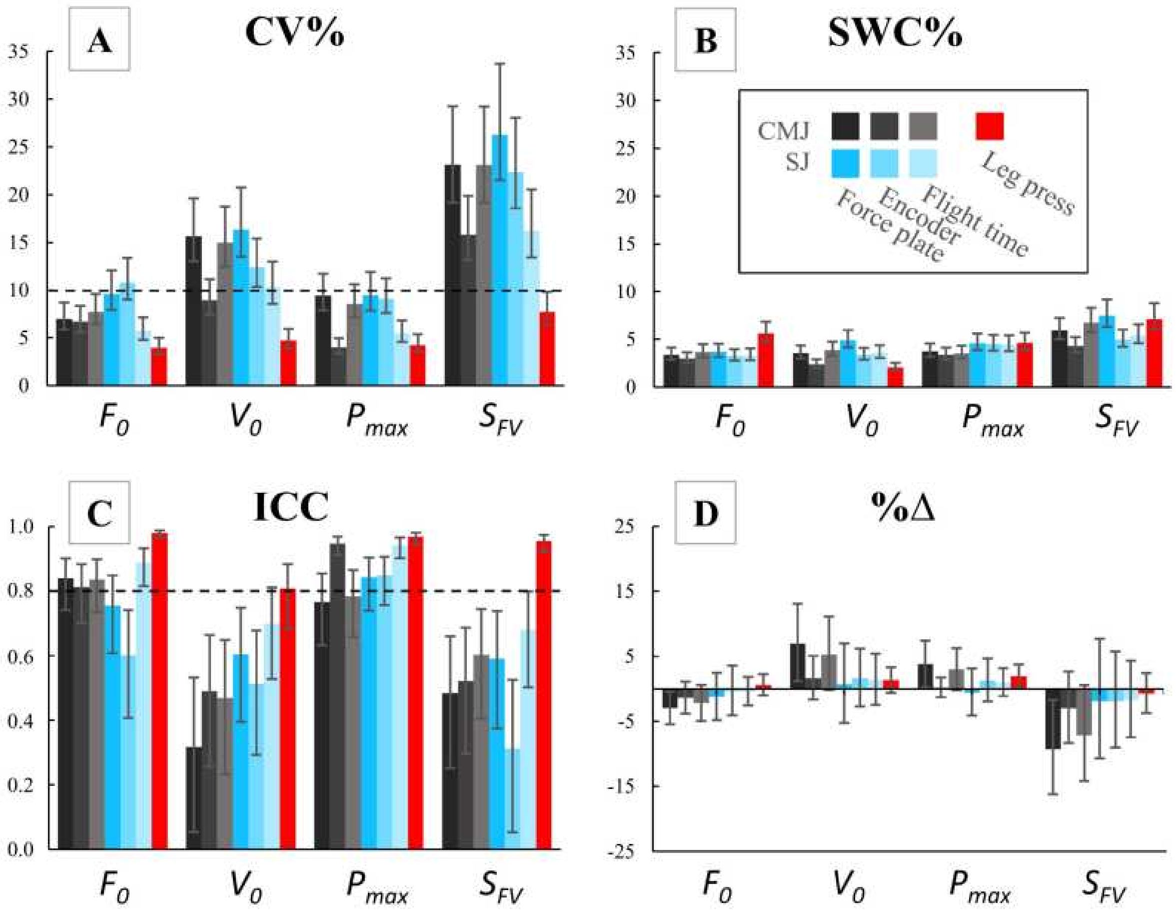

Figure 11. Analysis of reliability metrics for Force-Velocity variables. Subfigure A portrays the Coefficient of Variation (CV%), Subfigure B illustrates the Smallest Worthwhile Change (SWC%), Subfigure C shows the Interclass Correlation Coefficient (ICC), and Subfigure D presents the Mean Percent Change (%Δ). Error bars correspond to the 95% confidence intervals, and the dotted line delineates the threshold for acceptable reliability.

4.2 Agreement across methods (Study I)

These results are shown in detail in paper I and illustrated here in Figure 12 and Figure 13. The agreement between the different measurement methods for force (F_0) and power (P_{MAX}) was moderate to strong, as indicated by Pearson's correlation coefficients (r) ranging from 0.56 to 0.95 and the typical error of measurement (SEE%) being within 5.8 to 18.8%. However, the agreement for the velocity intercept (V_0) and force-velocity slope (S_{FV}) was weaker, with correlation coefficients ranging from -0.39 to 0.78, and the typical error of measurement is 12.2 to 37.2%. The mean bias for F_0 was minimal to moderate (-

6% to -14%, effect size (ES) -0.4 to 0.9); for P_{MAX}, it was small to large (-30% to -55%, ES -1.8 to 1.7), for V_0 it was trivial to very large (-35% to -70%, ES -2.8 to 2.2), and for S_{FV} it was small to very large (-32% to -165%, ES -1.2 to 3.8). The agreement between the force plate and flight time methods for force (F), velocity (V), and power (P) was generally strong, with Pearson's correlation coefficients (r) for F, V, and P being 0.93, 0.98, and 0.88, respectively. The typical error of measurement was 73.81 for F, 0.07 for V, and 130.12 for P, while the coefficient of variation (CV) was 5.50% for F, 7.78% for V, and 8.10% for P.

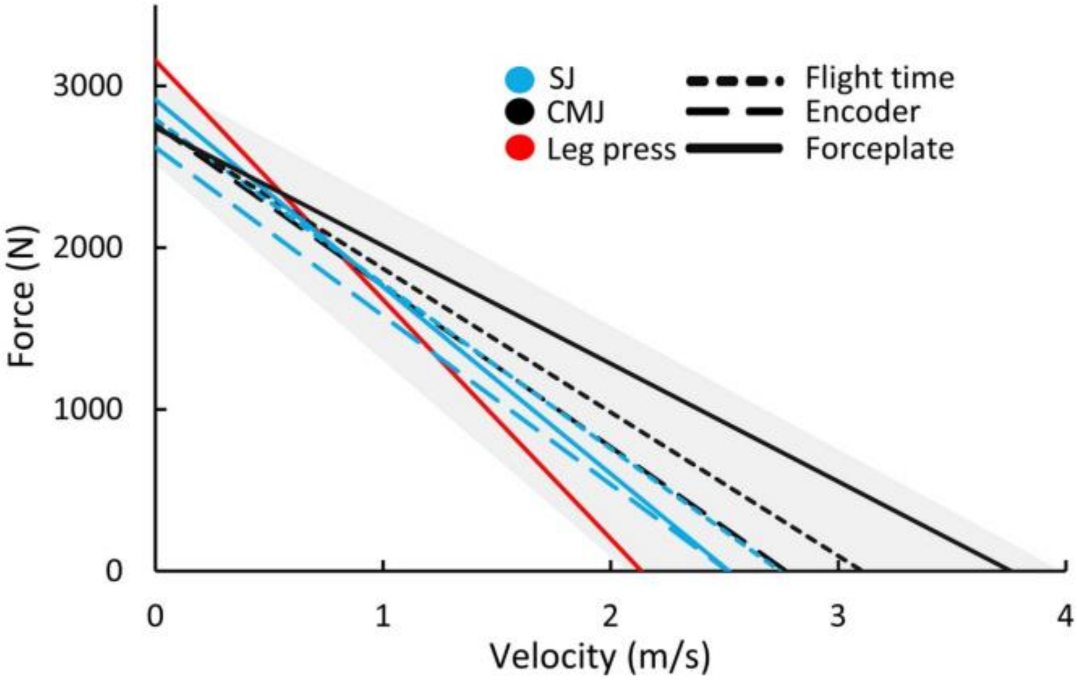

Figure 12. Presents the mean force-velocity profiles from all methodologies used in the study. The shaded region indicates the 95% confidence interval for the vertical jumps. SJ: Squat Jump, CMJ: Countermovement Jump.

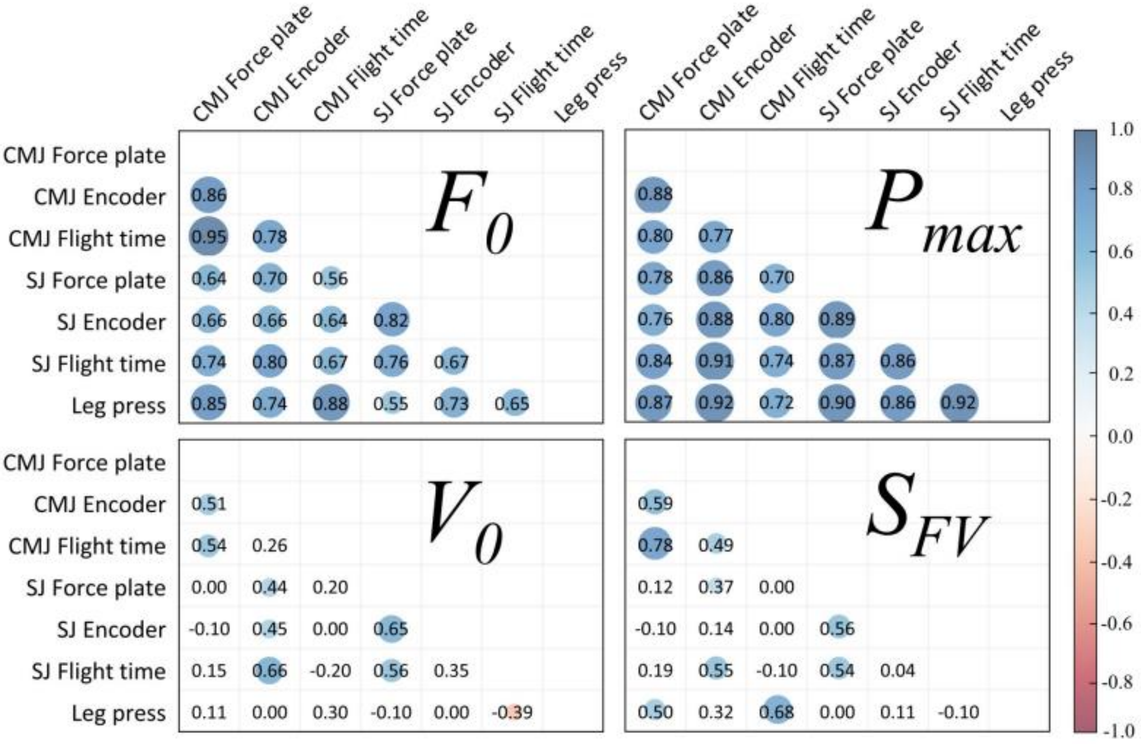

Figure 13. *Displays a correlation matrix with Pearson's r coefficients for the force-velocity profile variables (Theoretical maximal force (F_0), velocity (V_0), power (P_{MAX}), and the slope of the FV-profile (S_{FV})). Colored circles highlight significant correlations ($P<0.05$), with the size and color of each circle representing the corresponding r value (as detailed in the color legend provided with the figure). SJ - Squat Jump, CMJ - Countermovement Jump,*

4.3 Effectiveness of individualized training (Study II)

The following results are described in detail in paper II, summarized here, and illustrated in figures 14 & 15. The participants, on average, completed 75% (15 ± 3 out of 20) of the scheduled training sessions, with no significant differences in attendance between the groups (Toward, Away, and Irrespective) ($p > 0.05$). At baseline, five individuals were identified as having a velocity deficit, twenty as having a force deficit, and fifteen as being well-balanced. As indicated by a one-way ANOVA ($p > 0.05$), the training intervention did not result in any significant differences in FVIMB decrease between the groups training toward (−3 ± 21%), away (−6 ± 15%), or regardless of their FV-profile (−1 ± 16%)following the training intervention (Figure 14).

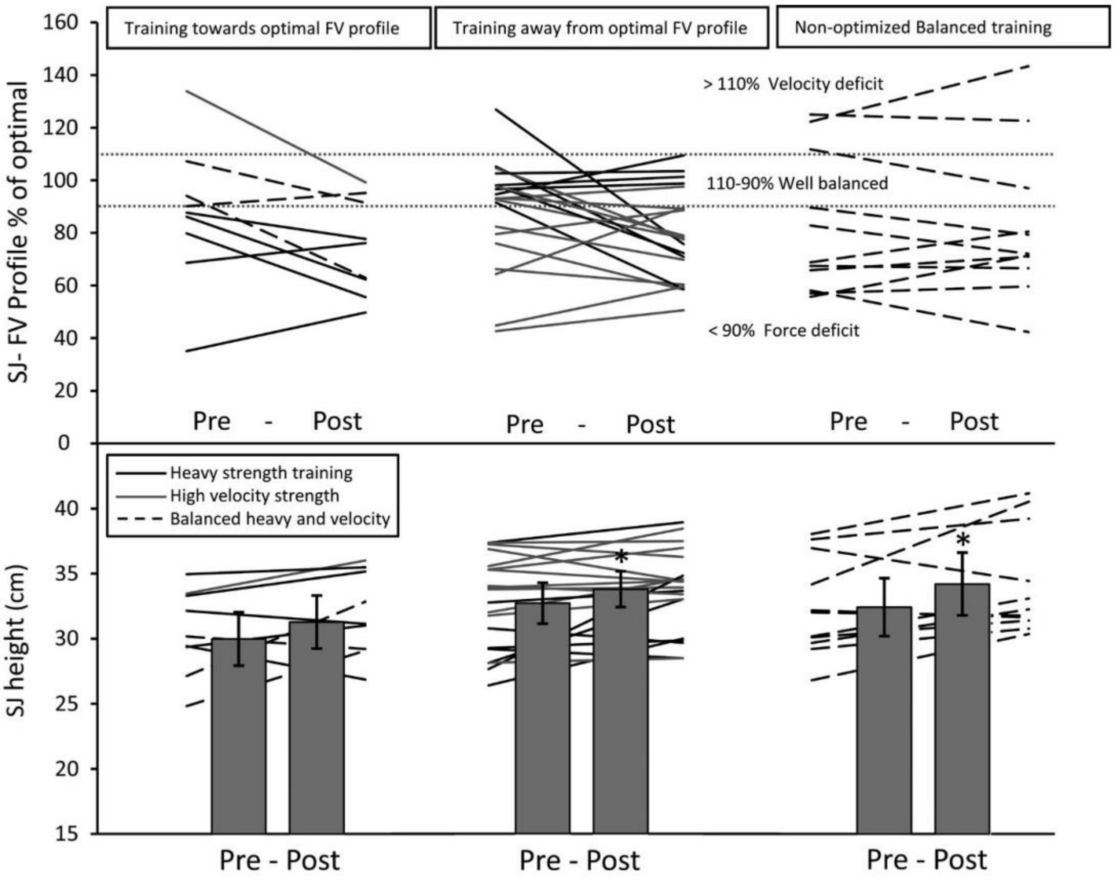

Figure 14. *The upper panel illustrates individual pre-to-post changes in the force-velocity (FV) profile, represented as a percentage of the optimal value among groups training toward, away from, or indifferent to the FV profile. The lower panel displays both individual and collective pre-to-post alterations in Squat Jump (SJ) height. Lines depict individual changes in the SJ-FV optimal profile and SJ height. Participants who were involved in heavy strength training are shown with black lines, those who focused on high-velocity strength training are denoted by gray lines, while broken lines represent participants who balanced their training between heavy and high-velocity strength. The error bars indicate the 95% confidence intervals. Statistically significant pre-to-post changes are marked with an asterisk (*$p < 0.05$).*

There were also no significant differences in any of the performance measures between the three groups (Figure 15). Changes in SJ-power were significantly related to changes in SJ-height ($r = 0.88$, $p < 0.001$) and CMJ-height ($r = 0.32$, $p = 0.044$), but unrelated to changes in 10m ($r = -0.02$, $p = 0.921$) and 30m sprint time.

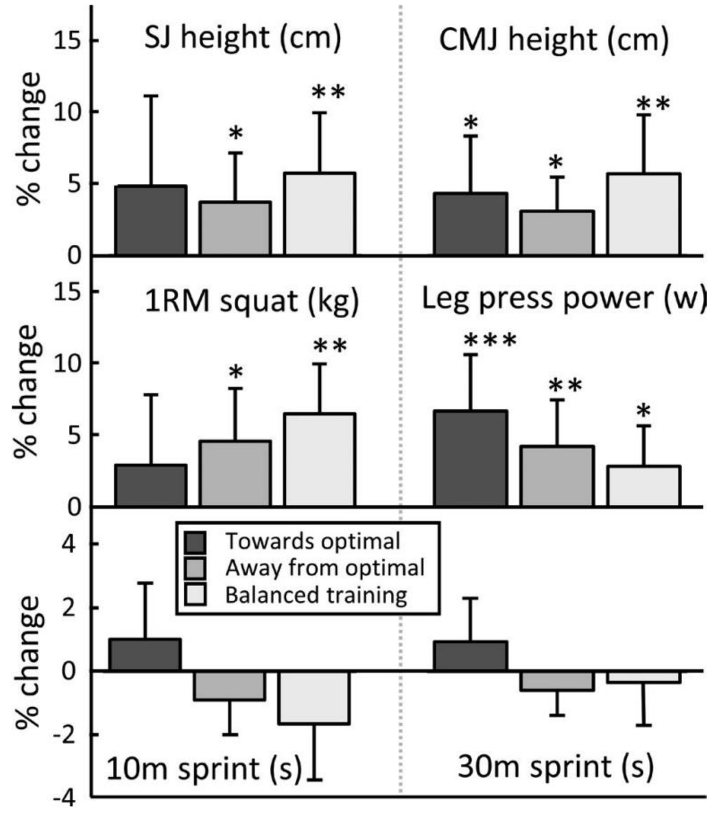

***Figure 15**. Percentage change in performance metrics from before to after the training, across three groups: those training toward, away from, or without specific reference (balanced training) to their initial theoretical optimal FV-profile. Here, SJ stands for Squat Jump, CMJ for Countermovement Jump, and 1RM for One Repetition Maximum. The units are as follows: Kilograms (Kg), Seconds (S), Centimeters (Cm), and Watts (W). The error bars correspond to the 95% confidence intervals. The asterisks denote the level of significance: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.*

Multiple linear regressions showed that 88% ($p < 0.001$) of the variance for the change score in SJ height was explained by changes in SJ- P_{MAX} ($B = 0.81$, $p < 0.001$), FV_{IMB} ($B = 0.13$, $p = 0.004$), body mass ($B = -1.31$, $p < 0.001$), and SJ baseline performance ($B = -0.004$, $p = 0.017$) (Figure 16).

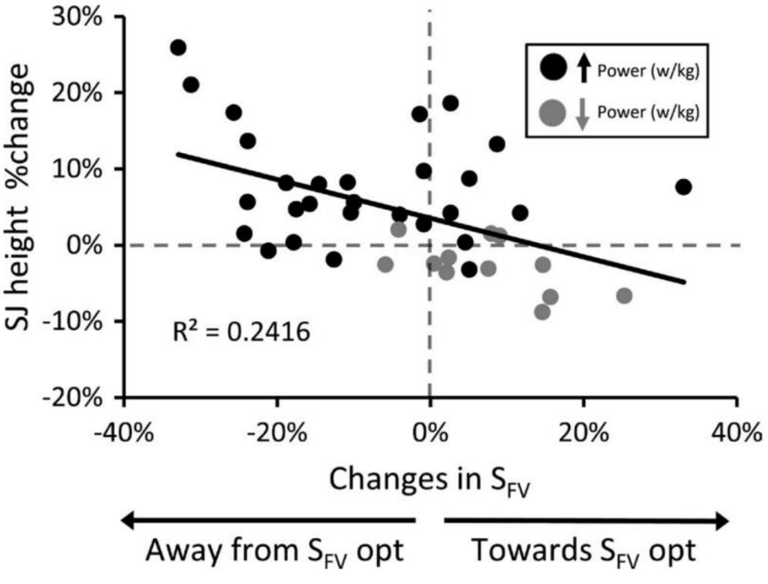

Figure 16*. Correlation between changes in Squat Jump (SJ) height and changes either toward or away from the optimal (opt) force-velocity (FV) profile. Black dots denote an increase (>0% change) in relative theoretical maximal power (Pmax/kg) in SJ, while gray dots indicate a decrease (<0% change) in relative Pmax. S_{FV} is the slope of the force-velocity profile.*

In sub-analyses for each training program (irrespective of FV-training groups) for the performance measures, participants training the heavy strength program increased leg press F_0 (5.9 ± 3.7%, p = 0.01) and P_{MAX} (7.7 ± 4.3%, p = 0.005). Participants training in the high-velocity program did not increase V_0 (2.8 ± 3.0%, p = 0.09). Participants who trained with the balanced heavy and velocity program had an increase in P_{MAX} (3.8 ± 2.6%, p = 0.01) but not in F_0 (2.3 ± 2.1%, p = 0.09) or V_0 (1.6 ± 1.7%, p = 0.08). The SJ-FV profiles showed strong linearity at all testing time points, with a coefficient of determination (R^2) of 0.97 ± 0.01.

4.4 Effects of being told you are in the intervention group (Study III)

The results indicated that the Placebo group showed a greater improvement in their 1RM squat compared to the Control group (Placebo: 5.7±6.4%, Control: 0.9±6.9%, Bayes Factor: 5.1 [BF10], p=0.025). Furthermore, the Placebo group also had an increase in muscle thickness compared to baseline (3.3±6.1%, BF10: 3.0, p=0.06), whereas there was no change from baseline in the Control group (-

1.9±14.0%, BF10: 0.3, p=0.89). The Placebo group had slightly higher adherence to the intervention compared to the Control group (Placebo: 82±18%, Control: 72±13%, Difference: BF10: 2.0, p=0.08) (Figure 17). The group difference in 1RM squat was significant even after adjusting for adherence (F=7.1, n2=0.19, p=0.013) and the SETS expectation level (F=5.4, n2=0.16, p=0.027).

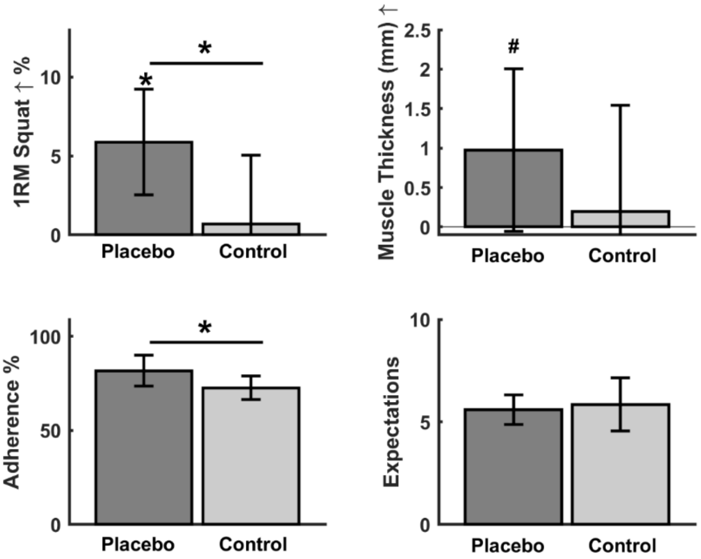

Figure 17*. Percentage change in 1RM (One Repetition Maximum) Squat, alterations in muscle thickness (measured in millimeters), adherence among groups (assessed as the percentage of completed scheduled training sessions), and median expectation (by the Stanford Expectations of Treatment Scale, SETS) for both the placebo and control groups. Statistically significant differences are marked with an asterisk (*p<0.05), while the hashtag (#) indicates (p<0.10). The horizontal line in the diagram signifies group changes. Error bars correspond to the 95% confidence intervals, except for SETS, where they represent the median along with the upper and lower quartiles.*

The study compared the placebo and control groups and found no significant differences in performance measures such as CMJ, 20-m sprints, or leg press power. The correlation between expectations and adherence to training was moderate (r=0.39, BF10: 3.8, p=0.013). Both groups had similar median expectations towards the intervention (Placebo: 5.6±0.7, Control: 5.9±1.1). However, the expectations of the lower quartile of the Control group were lower compared to Placebo (r=0.72, BF10: 2.1, p=0.033, Figure 17). There was a strong correlation between changes in muscle thickness and changes in 1RM squat (r=0.58, BF10: 6.3, p=0.025), but no correlation between adherence and changes in 1RM squat (r=-0.12, BF10: 0.2, p=0.53). Body mass didn't change in either group (Placebo: -0.2±1.7 kg, p=0.66, Control: 0.0±0.9 kg, p=0.96).

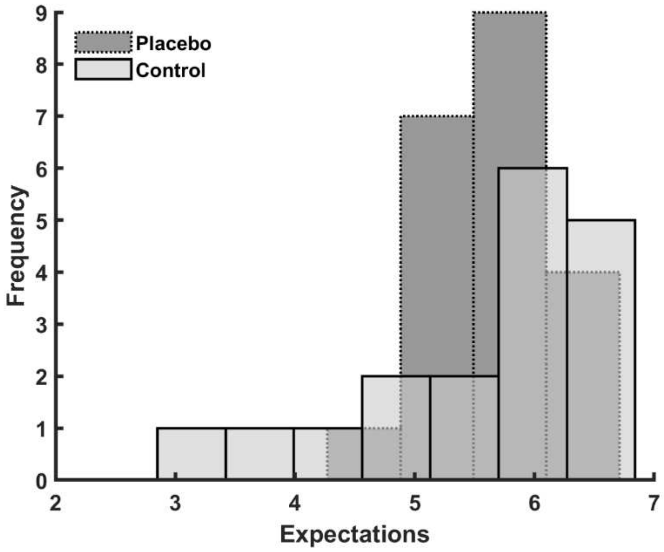

Figure 18. *Illustrates the distribution of expectation within the placebo and control groups. It provides a comparative overview of the expectancy patterns between the two groups.*

The results showed that there was no significant difference in any of the performance measures between the participants who underwent individualized training and those who underwent generic power training. Despite all participants in the individualized training group being deemed "velocity oriented" by the calculations and conducting high-load strength training, no differences were observed in the performance measures.

There were no significant differences in any of the performance measures between the placebo and control groups at the baseline assessment. The age of the subjects was also similar in both groups (Placebo: 22±4 years, Control: 22±5 years, p=0.83). Additionally, there was no difference in the baseline performance measures between subjects who dropped out and those who completed the study.

5 Discussion

The following section will discuss the finding from the three studies included in the thesis related to the use of force-velocity profiling in athletes. The findings from study-I showed that there are small but important differences between the FV variables obtained from different measurement methods, suggesting that practitioners and researchers should be aware of the limitations of measuring FV profiles, especially in obtaining V_0 and S_{FV}. The results from Study II and Study III suggest that the effects of individualized training based on FV profiling may not be as effective as originally hypothesized.

5.1 Athletic Performance Assessment using FV-profiles (Study I)

5.1.1 Test-retest reliability of the FV-variables

This is the first study to investigate the reliability of SJ and CMJ FV profiles obtained with a force plate, linear encoder, flight time calculation method, and leg press task between sessions. Moreover, to the author's knowledge, no previous studies have evaluated the test-retest reliability of the FV variables in highly trained and elite athletes. In accordance with prior studies in other populations, the current findings demonstrate largely good reliability for F_0 and P_{MAX} (CV<10%) and low reliability for V_0 and S_{FV} (CV >10%) during vertical jumping. (Cuk, Markovic et al. 2014, Meylan, Cronin et al. 2015, García-Ramos, Feriche et al. 2017, Zivkovic, Djuric et al. 2017, Valenzuela Pedro L. and Zigor Montalvo 2020). The reason for the difference in reliability for the FV variables has been earlier proposed to be caused by various factors. For example, Feeney et al. hypothesized that the low reliability of V_0 (and, by extension, S_{FV}) during vertical jumping might be a result of computing velocity from a force signal (Feeney, Stanhope et al. 2016). As velocity is the integral of acceleration and a less direct measure than force, it’s a reasonable hypothesis. However, from our results, it seems that the reliability of V_0 is independent of the measurement method, as we measured velocity by both the integral of acceleration (from the force-plate method), but also by using the positional transducer and flight time calculation. All demonstrate low reliability of V_0, reducing the likelihood that the variance in V_0 is the result of a computation error. Others have speculated whether the lower reliability in V_0 is caused by larger biological variation closer to the velocity intercept (Meylan, Cronin et al. 2015). However, this seems unlikely, based on the results in the present study, showing rather slightly higher variation in the heavy vs light loads conditions during jumping. Similar findings have been observed in other studies as well, that the measurement variations seem rather more constant across loading conditions (García-Ramos, Jaric et al. 2017). Importantly, the Leg-press exercises would be more accurate to compare across loads, as the technical demand does not change to the same degree as in loaded jumps. Indeed, even in the leg press exercises, we observe mostly identical typical errors across loads. Hence, the hypothesis that there is greater biological variation in the measurement close to V_0 seems unlikely. Further, García-Ramos et al. speculated that the low reliability of V_0 during jumping was influenced by the number of loads utilized and the "distance" of extrapolation (García-Ramos, Pérez-Castilla et al. 2018). Such speculations have also been noted by others (Cuk, Markovic et al. 2014). Interestingly, our data would support the notion that the loading range and extrapolation distance are of great importance. Indeed, in the jumping tasks, the loading range is closer to the F_0 intercept compared to the V_0 intercept. Where the reliability of F_0 is substantially better than V_0. Oppositely, in the leg press, the loading range utilized is much larger, and the loads are just as close to both intercepts. Such a wide loading range also corresponds to almost identical reliability in both intercepts. Hence, the results from our study reinforce the hypothesis that the lower reliability in V_0 compared to F_0 in jumping is caused mainly by the number of loads and distance of extrapolation. Such an explanation is at the root of mathematical, and not necessarily related to the measurements and biology of the athletes assessed. To further elucidate the proposed explanation, a simple mathematical simulation was run, illustrated in the figure below (Figure 19).

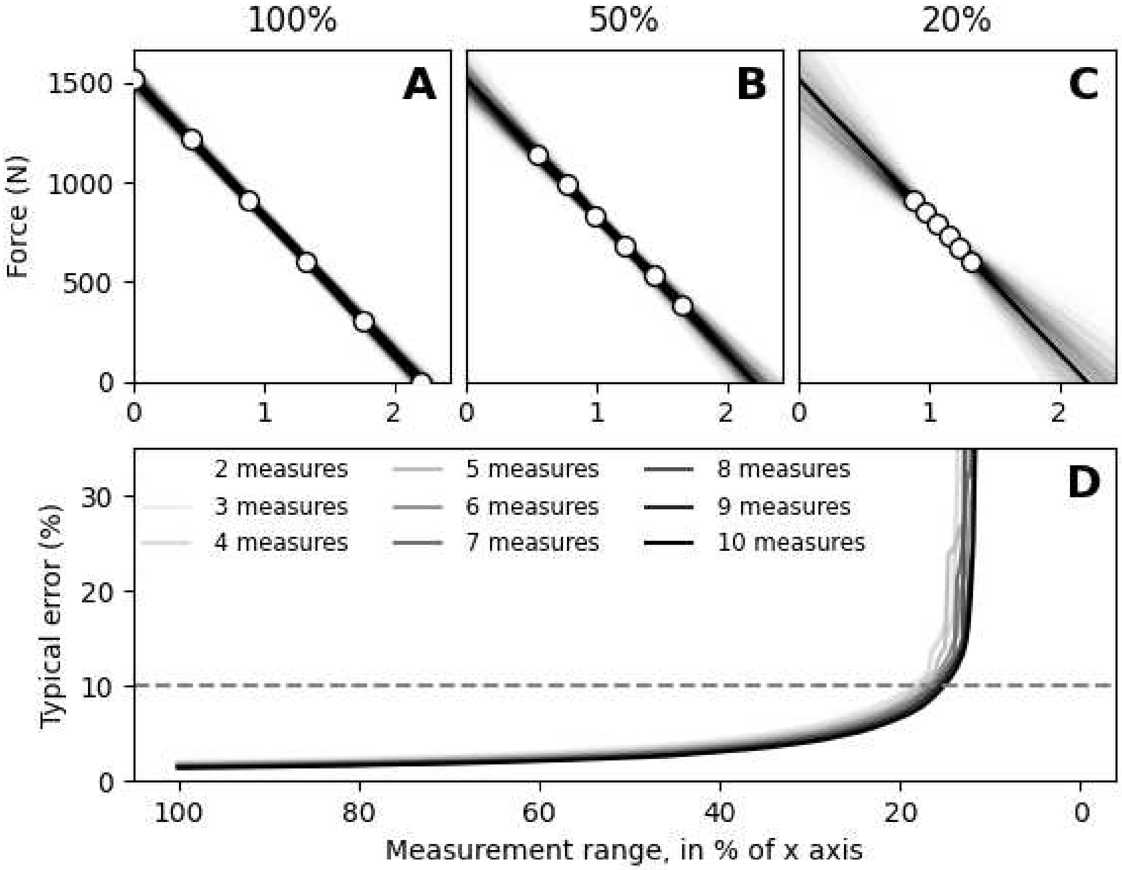

***Figure 19**. Sensitivity analysis concerning the impact of the range and number of loads used in the measurement of force-velocity profiles. The top row (Panels A, B, and C) presents scatter plots that display the relationship between force (N) and velocity (m/s) using three distinct data ranges, specifically 100%, 50%, and 20% of the total x-axis range, respectively. Each scatter plot includes six measurements with grey lines indicating the simulated errors. The bottom row (Panel D) shows an integrated analysis for all data ranges. Each line corresponds to a different number of measurements, ranging from 2 to 10 (where six is illustrated in the top panel). The dashed line at 10% is presented as the commonly used threshold for the typical error. The Typical error in the individual data points was 2%, corresponding to the data in the present thesis.*

5.1.2 Standardization and its Impact on Reliability

Another difference between the jumping and leg press tasks that potentially could influence the difference in reliability is the different standardization between the tasks. For example, the leg press task has a fixed seat position as well as a fixed movement path. Both potentially increase the consistency of the movement between loads. For example, recent investigations have studied how relative joint contributions during jumping change at increasing loads. Williams et al. (Williams, Chapman et al. 2018) observed that the hip joint contribution increased by ~5% at the expense of the knee joint contribution at increasing loads. Similarly, in a study by Wade et al., the hip joint contribution increased by ~7% at the expense of knee contribution (Wade, Lichtwark et al. 2018). Consequently, the conditions for the FV-test in jumping might change each time the mass increase, although the technical execution in terms of depth and joint angles are constant (Wade, Lichtwark et al. 2018, Williams, Chapman et al. 2018, Williams, Chapman et al. 2018). Hence, there is a possibility that such factors also play into the reliability of the jumping FV-profile outputs. The impact of standardisation is further corroborated by the findings of Valenzuela et al., who observed that the FV-variables obtained using a Smith machine were more reliable than those obtained using free weights (Valenzuela Pedro L. and Zigor Montalvo 2020). Accordingly, it is probable that the observed variations in the extrapolated variables V_0 and S_{FV} are the result of extrapolation error (i.e., small variations in the individual attempts are amplified by the "extrapolation distance") and a combination of technical/instrumental and biological variations. In addition to greater standardization compared to other tests, the broader load range in the leg press exercise decreases the requirement for force and velocity extrapolation, which explains the high reliability of all FV-variables.

5.1.3 Differences in Reliability between SJ and CMJ

Regarding differences in reliability between the jumping tasks, there were some slight differences between the SJ and CMJ that are worth discussing. Although the results are variable, it seems that the SJ has slightly worse reliability than CMJ in some of the measured variables. The reason for this slightly worse reliability in SJ vs CMJ might be due to both biological differences as well as technical measurement differences. For instance, SJ is susceptible to integration inaccuracies when determining velocity with the force plate approach (Pérez-Castilla, Rojas et al. 2019). Such errors are also present in the CMJ, but not to the same degree. The velocity is calculated as the integral of acceleration, which requires the assumption of a zero-starting velocity to be met. In theory, this should not be a problem, as the subject should be standing totally still before the eccentric phase in the CMJ and completely still at the bottom of the SJ position. However, in practice, several factors come into play. The subjects are not always able to stand completely still, especially in loaded conditions. Just imagine standing completely still in a predetermined squat position, with 80kg on the back, getting ready to jump as high as possible. With familiarization, the subjects get better, but it's not always perfectly still. Additionally, the calculation approach also will influence the integration start time. In this study, we used the 5SD of the steady stance weight, as commonly recommended, but such a threshold is neither perfect. For example, in instances where the steady stance weight is more variable, the threshold gets larger and oppositely smaller with less steady stance variation. Additionally, one could start the integration earlier in SJ before the subjects squat down. However, then one is susceptible to other errors again, such as cumulative errors in the integration, etc. If the goal would be to further investigate the difference in reliability between the CMJ and SJ conditions, one should rather use a force plate system integrated with a 3D-optical motion tracking system so that the equipment and measurement method would not differ between jumping conditions. Further, the difficulties with the starting position in the SJ vs. the CMJ are similar for the encoding equipment. As the measurement of average force and velocity starts the instance, the encoder registers positive displacement. Hence, small movements at the bottom of the squat could potentially cause inaccuracies in the encoder measurements as well. Oppositely, the flight time method calculates the average force and velocity, independent of such factors as the start of movement. This could be part of the reason the flight time method shows better reliability than the force-plate and encoder methods. Consequently, the low reliability of the SJ force plate and encoder methodology may be due to calculation inaccuracies and not physiological differences between the CMJ and SJ conditions. Therefore, when calculating FV-profiles from encoders and force plates during SJ, careful consideration should be given to the pause in the bottom (static position) of the squat to improve the detection of movement with this equipment (i.e., providing athletes with additional practice opportunities and/or familiarization).

5.1.4 Technical Differences in Encoder Software

In contrast to the SJ encoder measurement, the CMJ encoder measurements displayed markedly better reliability. The reason might partly be that there are fewer errors in determining the start of movement compared to the SJ. Additionally, there are some technical differences that also might come into play. For example, the accompanying Encoder software utilizes the whole positive displacement curve, including airtime, to get the average force and velocity data. This means that the variation in force and velocity variation between sessions will be harder to detect. Such calculation, where the airtime is included, is obviously theoretically incorrect, but from personal communications with the manufacturer, the calculations were implemented to improve the reliability of the measurement. So, the velocity is the time-average velocity from the start of the movement to the peak displacement in the air. And the average force is computed by multiplying the mass by the acceleration, where acceleration is the average velocity divided by the duration of the positive displacement. A more theoretically correct approach would be to take the derivative of velocity to get instantaneous acceleration over time and then use mass to calculate force with the formula $F = m/a$. Then one would get the time-dependent force, and thereafter one could calculate the time-average force over the push-phase. However, the problem with this approach in practice is that acceleration is the double derivative of position, where only tiny movements in the linear encoder line can cause large cumulative errors in the derived acceleration and, consequently, force values. Such errors are comparable to the problem with using the double integral of acceleration from a force-plate to get displacement, just that it’s in the opposite direction in terms of calculation. So, in practice, the manufacturer has simplified the calculation, which is likely the reason we observe more reliable values from the encoder vs the force-plate. However, this improved reliability inevitably comes at the cost of decreased accuracy and sensitivity of measurement. For example, in jumps with lighter loads (i.e., longer flight phase), the calculated force is then proportionally more affected by the body mass input vs the propulsive force. In contrast to heavier loads with shorter flight phases, the changes in propulsive force will be more accurately reflected. All these discussed factors above should be considered when interpreting the reliability form the encoder measurements. And it can be argued that the greater reliability observed from the encoder comes at the cost of decreased sensitivity to changes in performance.

5.1.5 Theoretical simplifications used in flight time method calculations.

Comparable to the encoder method, the flight time method showed improved reliability in some conditions compared to the force-plate method. This was especially evident in the SJ condition but not in the CMJ condition. This difference between SJ and CMJ is probably related to the issues with detecting the zero-starting velocity in the force-plate and encoder method in SJ, as discussed earlier. Further, similarly to the encoder method, the flight-time method uses some theoretical simplifications in the calculations to get the average force and velocity values. For example, assuming the push-off phase of the center of mass is the same as the distance from the great-trochanter to the tip of the toes. Moreover, when calculating force, this method relies on positional averages rather than time averages. This approach may limit its precision when computing power, as power represents the work rate, necessitating a time dimension for accurate measurement (Winter 2009). Similar simplifications are made in the velocity calculations where there is assumed a constant acceleration to get the dimension of time-average velocity (Winter 2009). Overall, in similarity to the encoder method, the flight-time calculation provides better test-retest-reliability due to several theoretical simplifications but at the cost of reduced validity.

5.1.6 Jump-height accuracy & magnification of FV-profile reliability

Together, the test-retest reliability of the FV profile depends on a variety of factors, such as biological, technical, and methodological variation. However, it is distinct from other common performance assessments in the sense that the distance/degree of extrapolation to the FV-intercepts also seems to affect the measured reliability. These limitations should indeed be considered when assessing FV-profiles, especially in tasks such as jumping. From our data, when the test-retest variation in the individual jumps is 5-10%, the FV-variables V_0 and S_{FV} cannot accurately be measured, regardless of the measurement used (using the loading range from 40-70% of F_0).

This thesis presents results on test-retest reliability that were published in 2021, and since then, there have been additional investigations conducted on this topic. The first of these studies examined the differences and between-day reliability of FV profiles obtained from constrained (Smith machine) and unconstrained (Free-weight) loaded vertical jumps, revealing meaningful differences and low between-day reliability for most FV variables (Valenzuela, Sánchez-Martínez et al. 2021). Comparable to our findings, the variability in jump height was between 5-10%, and the extrapolated variables were magnified. Especially the V_0 intercept, which had a CV% >30%. The authors caution against the poor reliability of the FV profile. In a subsequent study, the between-day reliability in SJ-FV profiles was investigated, where again, they found the FV-profile to be unreliable (CV >15%) (Kotani, Haff et al. 2021). Following the series of studies that have found the FV profile to be unreliable, Fessl et al. hypothesized that the reliability could be improved if the subjects had greater experience with jumping (Fessl, Wiesinger et al. 2022). Indeed, when they compared the reliability of the squat jump FV -profile between sports students and ski jumpers, the reliability was markedly different between the two cohorts. Specifically, the ski-jumpers had lower test-retest variation in jump height (CV ~3%) compared to the sport students and the earlier studies on the topic. This improved accuracy in jump height also led to a more accurate assessment of the FV profile. They still caution against the generally noisy FV-measures, but that through task-experience with jumping (more than just familiarization sessions), the reliability can be improved (Fessl, Wiesinger et al. 2022). Later the same year, a commentary article with an accompanying mathematical simulation further explored the topic of the test-retest reliability of the FV-profile (Samozino, Rivière et al. 2022). Indeed, in accordance with the literature, they found that the reliability of the FV-profile variables gets “magnified”. As we have discussed, the extrapolated FV variables will generally be less reliable than the individual measured datapoints. In the article, they recommend obtaining jump-height with an accuracy of <4-5% to get acceptable reliability of the FV-profile. It is here worth noting that the between day test-retest reliability of jump height is typically reported to be ~5% or higher (Hopkins, Schabort et al. 2001, Nuzzo, Anning et al. 2011, Lindberg, Solberg et al. 2022). Consequently, in practice, if one do not have the time to spend on extensive testing and training of the subject to get familiar with jumps, the jumping FV-profile might not be the best choice. As we have shown, an alternative approach would be to increase the loading range by using alternative exercises, such as the leg-press exercises. Another point worth considering in this context, is whether the “magnification” in the actual measurements is worth it to get the FV-profile in jumping. For example, if one is able to reduce the test-retest variability in the jumps to 2-3%, then instead of accepting a 3x variation of 6-9% (Samozino, Rivière et al. 2022) in the FV profile, maybe one should consider alternative tests and keep the excellent 2-3% accuracy? Nevertheless, it depends on what the intention of the test is; for example, there would be numerous alternative strength and power tests. But if the intention would be to obtain the “theoretical optimal jumping FV-profile”, there would be no alternative tests. Regarding the utility if this optimal profile, however, will we get into it later in the discussion.

5.1.7 Agreement across Methods

Regarding the agreement across methods, F_0 and P_{MAX} exhibited a large to almost perfect correlation across measurement methods, but the correlation between V_0 and S_{FV} varied from trivial to large. As mentioned in the introduction section, the difference between the term validity and agreement is that when we talk about validity, we usually want to have a comparison against a “gold standard”. In this context regarding jumping, the force plate would be considered the gold standard for force measurements. However, for the velocity measurements, an 3D motion capture system would be considered the gold standard, as it is much more accurate to calculate the center of mass velocity compared to the indirect method from the force-signal using the force plate (Lake, Lauder et al. 2012, Williams, Chapman et al. 2019). Nevertheless, commonly in the literature, the force-plate measurements are used to validate other measurements for both force and velocity measurements. Hence, in interpreting the results from the present study, we can consider the force-plate the “most valid” method and use this as the criterion measure.

Giroux et al. previously evaluated the agreement of force plates, accelerometry, linear position transducers, and the flight-time computation approach for measuring force and velocity during squat jump (Giroux, Rabita et al. 2015). They concluded that all methods agreed and suggested that the methodologies may be relied upon to accurately quantify the force-velocity profile. Their study included both inactive individuals and athletes, which is a strength in this situation. However, the Force-Velocity Profile (F_0, V_0, P_{MAX}, and S_{FV}) of the participants were not assessed(!). They simply evaluated the average force and average velocity from single repetitions. As we have seen earlier in the discussion, the variation in the extrapolated variables is much greater than in the individual measurements. Hence, it is not appropriate to either conclude that the FV profiles agree across the methods nor is it appropriate to compare with the results of studies measuring the extrapolated FV variables. A few years later, Garcia-Ramos et al. studied the same assessment methods, force-plate, transducer, and flight-time computation method (García-Ramos, Pérez-Castilla et al. 2019). As with the Giroux experiment, they discovered that the individual force and velocity results were consistent across all methodologies. However, when these values were extrapolated to construct the FV-profiles, the disparities were bigger. Interestingly, in accordance with the results from the present study, they observed strong correlations for F_0 and P_{MAX} and trivial correlations for V_0 and S_{FV} across methods. Like the current study, the poor agreement between V_0 and S_{FV} was attributed to the extrapolation error (García-Ramos, Pérez-Castilla et al. 2019). As a result, they cautioned against the usage of linear transducers and advised caution while measuring jump height, which is utilized in the procedure for calculating flight time.

5.1.8 Validity and Limitations of Flight-Time and encoder Method

An study by Jiménez-Reyes et al. (Jiménez-Reyes, Samozino et al. 2017) reported high agreement (r: 0.98–0.99) between flight time and the force plate method for the FV-variables. These findings are in stark contrast to our findings and the literature. For example, the data from Giroux et al. showed a correlation of 0.98 and 0.88 for individual force and velocity values, respectively, comparing the flight-time method to the force-plate measurement. With a CV% of 3.7 for force and 11.4 for velocity, these values are comparable to what we also observed for the individual force and velocity values, with a correlation of 0.93 and 0.98 and a CV% of 5.5 and 7.8 for force and velocity, respectively. In contrast, Jiménez-Reyes et al. reported a correlation of 0.99, 0.99, and a CV% of 0.7 and 1.4 for force and velocity, respectively. The relative difference in the CV% across these studies is >5 times, which is definitively notable. These discrepancies might be caused by a variety of factors. For example, differences in participant populations, testing protocols, or data processing techniques. Jiménez-Reyes et al. included high-level sprinters and jumpers, which might indicate that they were more familiar with jumping compared to the mixed samples used in our and the study by Giroux et al. Based on the results and discussion in the reliability section, the impact of familiarity with jumping might play an important role in the accuracy of these measurements. The flight-time method computes force and velocity based on the height of the jump, which is again calculated from flight-time measurements (Jiménez-Reyes, Samozino et al. 2017). Hence, any small variations in the flight-time measurement will inevitably affect the agreement compared to the force-plate method. Consequently, the validity of the flight-time calculation is depended on how well the assumptions in the calculations are met, including both the accuracy of the flight-time and the push-of measurements. A factor that could potentially influence the accuracy of the flight-time calculation is the sampling and measurement of the flight-phase. In our study we sampled the fore-plate at 200hz, where both Jiménez-Reyes et al and Giroux et al. sampled at 1000Hz (Giroux, Rabita et al. 2015, Jiménez-Reyes, Samozino et al. 2017). Hence, it is more likely that the potential errors in the flight time reside elsewhere. As commonly discussed in the literature (Attia, Dhahbi et al. 2017), the most frequent errors observed in flight time estimates of jump height reside from the difficulty of controlling the subject's posture at landing. Only a slight bend in the knees or ankles will result in inaccurate jump heigh estimates. Hence, to obtain accurate flight-time measurements, and consequently jump height, force, velocity and FV-variables, the subjects would need to be closely familiar with this form of jumping. It is highly likely that Jiménez-Reyes et al. (Jiménez-Reyes, Samozino et al. 2017) were more aware and carful in considering these factors is their validation experiment, compared to ours study and that by and Giroux et al. Consequently, the interpretation of the validity of the flight-time method should take such limitations into account. It could be argued that the findings by Jiménez-Reyes et al. better represent the validity of the calculations themselves (Jiménez-Reyes, Samozino et al. 2017), whereas the other studies mentioned would better reflect the accuracy we can expect in practice. Moreover, with respect to the validity of the theoretical calculations, there are some limitations that are worth noting in this context as well. For example, the assumption of constant acceleration, which inevitably will decrease the validity of the flight time method as variations in average force and velocity during the push-off phase are not necessarily related to jump height variations (Cormie, McBride et al. 2009, Mitchell, Argus et al. 2017, Janicijevic, Knezevic et al. 2019, Janicijevic, Knezevic et al. 2019). Such limitation in the validity of the flight-time calculations, have indeed been recently also shown in a simulation study on the topic of force-velocity profiling in jumping (Bobbert, Lindberg et al. 2023).

In contrast to previous research demonstrating an overestimation of V_0 measured with an encoder versus a force plate (72.3%; (García-Ramos, Pérez-Castilla et al. 2019, Williams, Chapman et al. 2019)), we observed an underestimation for the CMJ condition (-23%). The attachment point at the bar explains the overestimation of velocity during mild loading conditions in previous studies, as the bar velocity is greater than the center-of-mass velocity during jumping (García-Ramos, Pérez-Castilla et al. 2019, Williams, Chapman et al. 2019). Because the velocity from the encoder used in this study is based on the entire positive displacement trajectory (including the flight phase), the average velocity is reduced. This, in conjunction with the extrapolation error, partially explains the greater agreement between the force plate and encoder for F_0 and P_{MAX} than for V_0 and S_{FV}. Practitioners and researchers should be aware of the limitations of linear encoders when measuring FV-profiles, particularly when attempting to derive V_0 and S_{FV}.

5.1.9 Biomechanical Differences across Exercises

Comparing a leg press task to the squat task, Padulo et al. (Padulo, Migliaccio et al. 2017) observed an underestimation of V_0 (-46%) and an overestimation of F_0 (21%). The underestimation of V_0 is likely due to biomechanical differences, as the squat movement entails a greater contribution from the hip joint, resulting in a higher system velocity (Padulo, Migliaccio et al. 2017). In addition, the ankle joint contributes approximately 30% of the work during jumping (Williams, Chapman et al. 2018). Due to the plantarflexed orientation of the ankles in the leg press, the contribution from the ankles is likely to be lower for the leg press vs. the squat. Such biomechanical differences likely explain why the leg press shows the greatest difference from all tested methodologies. Furthermore, the absence of inertia in the pneumatic resistance in the present leg press apparatus also likely explains some of the differences (Frost, Cronin et al. 2010). The push-off distance has a significant effect on the extrapolated V_0 during the leg press

(Bobbert 2012), where it was previously argued that comparisons between individuals should only be made when participants perform the vertical jumps with their usual or optimal push-off distance (Samozino, Morin et al. 2010). In our study, the initial push-off distance during jumping was self-determined, whereas the push-off distance in the leg press was standardized, which may further influence the correlation between V_0 in the leg press and jump exercises. In addition, as demonstrated by Bobbert (Bobbert 2012, Bobbert, Lindberg et al. 2023), the assumption of a perfectly linear FV relationship is not correct, which further influences the correlations observed.

It is important to consider the limitations of various measurement methods when assessing FV profiles. While force plate measurements can be considered the "most valid" method, researchers and practitioners should be cautious when interpreting results from other methods, such as linear encoders or flight-time calculations, especially when extrapolating V_0 and S_{FV}. Familiarity with jumping, participant populations, testing protocols, and data processing techniques may all contribute to discrepancies in results. Understanding biomechanical differences in exercises, such as the leg press versus the squat, is also crucial in interpreting FV profiles.

5.2 Individualized Training Prescriptions (Study II & III)

5.2.1 Individualized training based on the FV-profile.

The primary finding of study II was that training towards a theoretical optimal SJ-FV-profile was just as beneficial for developing SJ and CMJ height, 1RM strength, 10 and 30 m sprints, and leg press power as training away from or regardless of individuals' starting FV-profiles. In addition, increasing SJ- P_{MAX} was positively linked with increasing SJ and CMJ height but not with increasing 10 and 30 m sprint times.

Currently, to the authors' knowledge, six experimental studies have evaluated the effectiveness of individualized training based on force-velocity profiling (Jiménez-Reyes, Samozino et al. 2017, Rakovic, Paulsen et al. 2018, Álvarez, García et al. 2019, Jiménez-Reyes, Samozino et al. 2019, Simpson, Waldron et al. 2020, Zabaloy, Pareja-Blanco et al. 2020). Two of the studies did not find any effects in favor of individualizing training based on the FV-profile

(Rakovic, Paulsen et al. 2018, Zabaloy, Pareja-Blanco et al. 2020). Notably, the study by Rakovic et al. was performed as a pilot project in sprinting and is not directly comparable to the jumping tasks and hence should be interpreted accordingly. The study by Zabaloy at al., on the other hand, did utilize the theoretical optimal FV-profile approach proposed by Samozino et al. Nevertheless, they did not find any significant group differences in any of the performance measures between the non-individualized group vs the individualized training group (Zabaloy, Pareja-Blanco et al. 2020). They did observe some within-group changes (i.e., pre-post improvements) and framed the findings as "individualisation of a training programme based on FV_{IMB} could be an effective method to improve sprint and strength performance". Only two of the four remaining investigations had a control group conducting a "non-optimized" training regimen for comparison (Jiménez-Reyes, Samozino et al. 2017, Álvarez, García et al. 2019, Jiménez-Reyes, Samozino et al. 2019, Simpson, Waldron et al. 2020). The study by Jiménez-Reyes 2019 aimed at looking at the time it would take to reach the optimal FV-profile and does not give us information on whether the approach would be superior to traditional strength and power training. Similarly, the study by Álvarez et al. did neither include a comparison against traditional strength and power training. Both groups consisted of ballet dancers, and only the intervention group performed additional resistance training. Oppositely, in the study by Simpson et al., they included both a group training to reduce their theoretical FV-imbalance and a group performing general strength and power training. In accordance with the proposed theory, they found the individualized training approach to be more effective in improving jumping performance compared with generalized training. Similarly, the first study on the topic by Jiménez-Reyes in 2017 also found the individualized approach to be more effective for improving jumping performance compared to general strength and power training.

Although the literature shows mixed results, in comparison to the studies finding positive results, we only observed small improvements in jump height and no clear differences between groups (Jiménez-Reyes, Samozino et al. 2017, Álvarez, García et al. 2019, Jiménez-Reyes, Samozino et al. 2019, Simpson, Waldron et al. 2020). The small improvements may be attributable to the lower training attendance in the present study, where individuals completed ~15 sessions over a 10-week period (compared to 18 sessions in Jiménez-Reyes, et al. (2017)). Additionally, the training status of the participant might also have influenced the results, where it is well known that the expected improvements diminish with increasing the training status of the participants (Suchomel, Nimphius et al. 2018). Intriguingly, both the "away" group and the non-optimized balanced group in study II increased their jump height (ES=0.30 and 0.50, $p<0.05$, respectively). In contrast, Jiménez-Reyes et al. (Jiménez-Reyes, Samozino et al. 2017) and Simpson et al. (Simpson et al. 2020) found that the balanced (non-optimized) group did not enhance jump height (ES=0.14 and 0.12). The absence of changes in the "non-optimized" group was ascribed to wide individual variability in training response because of not targeting the FV_{IMB} (Jiménez-Reyes, Samozino et al. 2017). This is highly intriguing given that all previous strength and power training interventions have been conducted regardless of differences in FV-profiles and have generally shown small to large effect sizes in jump height and power after various resistance and power training regimens (Markovic 2007, Hackett, Davies et al. 2016, Lesinski, Prieske et al. 2016, Stojanović, Ristić et al. 2017, Slimani, Paravlic et al. 2018). It is unknown whether the participants and coaches in the "optimized" and "non-optimized" groups in the studies by Jiménez-Reyes et al. and Simpson et al. were aware of their group allocation, which could have played a significant role in the efficacy of the training due to a potential nocebo and placebo effect (Beedie, Benedetti et al. 2018).

5.2.2 Influence of Force-Velocity “imbalance” on jump height.

In the study by Simpson et al., the athletes decreased their FV_{IMB} by approximately ~10 percentage points while at the same time increasing both strength and power. According to the calculations presented by Samozino et al.(Samozino, Di Prampero et al. 2012), the ten percentage points in FV_{IMB} can account for ~1% (0.4 cm) of the changes in jump height (Illustrated in Figure 20). Similarly, in the study by Jiménez-Reyes et al. (Jiménez-Reyes, Samozino et al. 2017), the average FV_{IMB} reduction was ~25 percentage points which would relate to an increase in jump height of around ~2% (0.6 cm). Both studies attribute the large increases in jump height (2.9 and 4.1 cm respectively) to the superiority of the FV-training approach and conclude: «the present results showed that reducing FV_{IMB} without even increasing P_{MAX} lead to clearly beneficial jump performance changes.» .

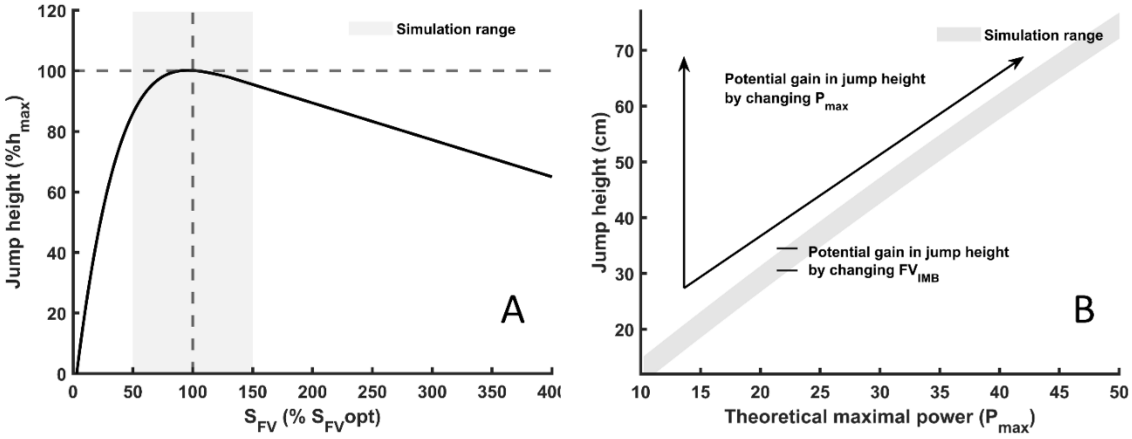

Figure 20. *(A): The x-axis represents the relative difference between the optimal force-velocity (FV) profile and the actual FV-profile, expressed in % (FV_{IMB}). The y-axis represents the difference between the actual and predicted jump height for the optimal FV-profile. The data are generated from the equations by Samozino et al. 2012, using a random number generator, producing input values for F_0 between 20-60 N/kg and V_0 2-4 m/s with an Hpo of 0.45m. (B): The x-axis plots the theoretical maximal power (P_{max}), and the y-axis plots the unloaded jumping height. The data are based on the same simulation as figure panel A, where the grey area represents the range of available jump height for a given P_{max}*

The lack of improvements (in jump height) in the “non-optimized” control groups was attributed to large individual variations in training response due to not targeting the individual FV_{IMB} (Jiménez-Reyes, Samozino et al. 2017). However, based on the theoretical framework presented by Samozino et al. (Samozino, Di Prampero et al. 2012), the increases in jump height that can be related to the 25% change in FV_{IMB} is, at best trivial (Figure 20). The opposite is also true: the lack of improvements due to not targeting FV_{IMB} is also, at best trivial. The inconsistencies in previous findings (Jiménez-Reyes, Samozino et al. 2017, Rakovic, Paulsen et al. 2018, Álvarez, García et al. 2019, Jiménez-Reyes, Samozino et al. 2019, Simpson, Waldron et al. 2020, Zabaloy, Pareja-Blanco et al. 2020) must therefore lie in experimental differences, as the theoretical framework cannot account for the lack of increases in the control-groups nor for the large increases in the experimental groups.

In our study, we were unable to detect any significant changes in the FV_{IMB} of the groups training towards or away from their optimal FV-profile. This lack of change can probably be attributed to the large measurement variation in the FV-slope, discussed earlier, in combination with small changes after the training intervention. Nevertheless, following the previous paragraph, any reduction in FV_{IMB} would have minuscule effects on jump performance. Indeed, from a multiple regression, we found the effect of FV_{IMB} on changes in SJ height to be relatively small (B=0.14) compared to that of P_{MAX} (B=0.84). Additionally, as presented in the results chapter, without accounting for P_{MAX}, the reduction in FV_{IMB} was even associated with decreased jump height. That means, in practice, that the subjects that got closest to their "optimal" profile saw the worst improvements, and some even decreased their jumping performance(!).

5.2.3 Jump Height and the FV-profile: Predicting vs. Explaining

In one of the first papers proposing the optimal FV-profile, Samozino et al.(Samozino, Di Prampero et al. 2012) stated: "we think that the F–v profile represents a muscular quality that has to be considered attentively not only by scientists working on muscle function during maximal efforts but also by coaches for training purposes" (Samozino, Di Prampero et al. 2012). Consequently, they suggest that deviations from the optimal FV-profile can be used to prescribe training loads to optimize jumping performance: "Vertical profiling will provide information as to what physical capabilities should be developed to improve ballistic push-off performance and as to the maximal levels of force and velocity of the athlete's neuromuscular system." (Morin and Samozino 2016). However, at the most fundamental level, the FV-profile is influenced by a multitude of factors, as it is measured from system velocity and ground reaction forces. Moment arms, joint angles, push-off distance, body weight, anthropometrics, and segmental dynamics are all factors influencing the measured FV profile, where all these factors are unrelated to muscular properties (Samozino, Di Prampero et al. 2012, Bobbert, Lindberg et al. 2023). A recent simulation study explores the issues of whether the force-velocity profile and its characteristics can be related to the intrinsic force-velocity relationship (Bobbert, Lindberg et al. 2023). From the simulation study, it were concluded that the force-velocity profile is specific for the task and that it does not represent the intrinsic force-velocity relationship. In practice, we can illustrate the task-specificity of the FV-profile by for example changing the push-off distance. As shown in Figure 21, FV-profiles measured in a single subject for 3-different push off distances; the actual as well as the "optimal" FV-profile vary by 73% and 83% among conditions, respectively. Here, the intrinsic properties are identical, but only one condition (Push-off distance) were changed. Consequently, the descriptive nature of the theoretical framework regarding the optimal FV-profile should not be confused with an predictive ability (Shmueli 2010).

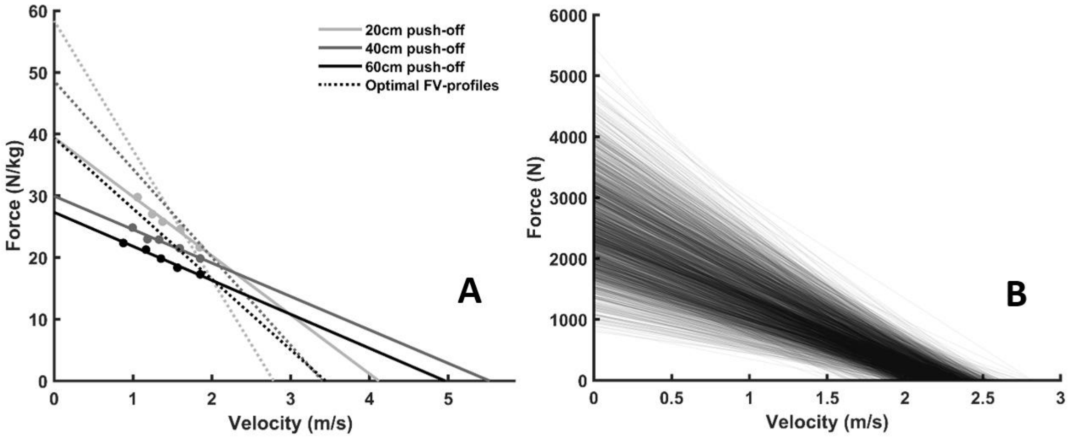

***Figure 21**. (A): Data from 1 subject's jumping FV-profile from 3 different push-off distances, 20-40 and 60 cm. The dotted lines are the optimal FV-profiles as calculated by* Samozino et *al. 2012. The y-axis shows time-averaged ground reaction forces, whereas the x-axis shows the time-averaged system velocity of the subject jumping with the loads 0,20,40,60, and 80 kg. (B): The figure shows multiple FV-profiles obtained from different athletes using a leg-press dynamometer (Lindberg, Solberg et al. 2021, Nysether, Hopkins et al. 2023). Both force and velocity are obtained from time-averaged values from the entire push-off phase.*

The framework can describe the relationship between ground reaction forces and system velocity, as well as the potential jump height of an athlete given if the theoretical optimal FV-profile is reached. However, based on the framework, we cannot infer whether it is possible for the athlete to reach this theoretical optimal FV-profile, nor infer which factors are responsible for the observed FV-profile, nor infer which muscular properties have the greatest potential for changes. For example, the between-subject variation in force (~300%) has been shown to be larger than the between-subject variation in the velocity portion (~40%) of the FV-profile (Dorel 2018). The same is true for a multitude of athletes from different sports tested at the Norwegian Olympic training center, indicating that the force part of the FV profile has a substantially greater potential for change (Figure 21). Indeed, it is observed that the force portion of the FV profile generally changes to a greater degree after training than the velocity portion of the FV-profile (Moss, Refsnes et al. 1997, Toji, Suei et al. 1997, Toji and Kaneko 2004, Crewther, Cronin et al. 2005, Cormie, McCaulley et al. 2007, Cormie, McGuigan et al. 2010). Consequently, there is little reason to believe that there is equal potential for changes in the force compared to the velocity portion of the FV-profile. Furthermore, strength and power athletes who generally have the greatest jump heights (and are probably close to their genetic potential) are shown to possess theoretical FV-imbalances (i.e., evident by developing peak power at loads different than body weight) (Haugen, Breitschädel et al. 2020, Loturco, McGuigan et al. 2021). The FV_{IMB} approach will then describe the FV-profile that optimizes jump height and suggest which part of the FV-curve needs to change. However, the largest increases in jump height will inevitably be observed after the training intervention that targets the capacity with the largest potential for change. Unfortunately, such information cannot be inferred from a descriptive mathematical model. Hence, we would argue that the FV_{IMB} approach lacks the predictive nature it was originally hypothesized to have (Shmueli 2010). In the future, simulation models on the topic would be useful, as we could then exclude a lot of the practical issues with running training experiments, such as measurement accuracy, placebo effects, etc.

5.2.4 The effects of different training programs

Regarding the training effects of the various programs in study II, it appears that the heavy strength and balanced training programs induced the hypothesized adaptations, i.e., an increase in 1RM and leg press power, which is consistent with the literature. (Kaneko, Fuchimoto et al. 1983, Toji, Suei et al. 1997, Aagaard, Simonsen et al. 2002, Toji and Kaneko 2004). In contrast, the high-velocity program had no noticeable effect on V_0 in the leg press. The workouts in the velocity program consisted of light weights and high-velocity movements with a training volume equivalent to earlier research. (Jiménez-Reyes, Samozino et al. 2017). Nevertheless, it is plausible that the subjects were regularly exposed to high-velocity movements from their respective sports and, as a result, did not receive enough stimuli for velocity-related adaptations. (Crewther, Cronin et al. 2005). As discussed in the previous paragraph, when comparing low-load training to heavy or mixed-load training, force adaptations tend to be greater than velocity adaptations on the FV-curve. (Moss, Refsnes et al. 1997, Toji, Suei et al. 1997, Toji and Kaneko 2004, Crewther, Cronin et al. 2005, Cormie, McCaulley et al. 2007, Cormie, McGuigan et al. 2010). Therefore, it is plausible that heavy loading provides a more strong stimulus and/or that force-generating capabilities are more responsive to adaptation at low velocities than at high velocities. (Crewther, Cronin et al. 2005). It's interesting to note that individuals in the current study who exercise with a mix of heavy and light loads tend to demonstrate higher improvements in power over the whole FV-curve than those who train with either heavy or light loads alone. (Moss, Refsnes et al. 1997, Toji, Suei et al. 1997, Toji and Kaneko 2004, Cormie, McCaulley et al. 2007, Cormie, McGuigan et al. 2010).

5.2.5 Relationship between FV_{IMB} and various Performance outcomes

One of the aims of study II was to explore the effectiveness of individualized training on several performance outcomes that are typically tested and of relevance to coaches, such as CMJ height, maximal strength, 10, 30 m sprint, and power measures in movements and other than the SJ. As presented in the results chapter, there were no significant differences in any of the performances between training groups. In addition, changes in FV_{IMB} were unrelated to changes in CMJ and sprinting performance, while changes in P_{MAX} were associated with changes in CMJ performance. Changes in FV_{IMB} and the slope of the FV-profile without a corresponding rise in P_{MAX} indicate a decrease in power at either high or low velocities. Complex athletic actions necessitate power output at a variety of joint angles and contraction rates, where a right shift of the entire FV-curve and improvement of power at both high and low velocities would likely be advantageous. As discussed in the earlier paragraphs, if the FV_{IMB} is at root only a mathematical description without predictive power, it is not strange that changes in this variable were unrelated to any other performance outcomes.

5.2.6 Studies on the Placebo Effect

The aim of Study III was to investigate the placebo effect in relationship with the individualized training approach. Per the author's knowledge, this is the first study to explore the placebo effect because of modifying participants' expectations of a training intervention. The primary finding of the study was that, although receiving matching training, participants in the intervention group (Placebo) increased their 1RM squat more than those in the control group (Control). In addition, the placebo group had an increase in muscle thickness that was significantly associated with changes in leg strength. The present study's effect size (ES: 0.26) is slightly smaller compared to that reported in the literature. A recent review on the subject evaluated the findings of placebo studies in sports science and reported a pooled effect size of 0.37, which included the effects of a range of placebo treatments (Hurst, Schipof-Godart et al. 2020). The type of treatment with the largest observed treatments was placebo anabolic steroids with an effect size as large as 1.44 (Ariel and Saville 1972, Maganaris, Collins et al. 2000, Hurst, Schipof-Godart et al. 2020). The smallest effects observed were observed from fake sports supplements, with effects comparable to the present study (ES: 0.21) (Hurst, Foad et al. 2017). It is observed that the type of placebo influences the participant's expectations and hence the observed effects (Gu, Gu et al. 2017). For example, sham surgeries have been shown to induce very strong placebo effects (Gu, Gu et al. 2017), and placebo injections exhibit stronger effects than placebo pills (Kaptchuk, Goldman et al. 2000). The expected placebo effect would, hence, be expected to be lower in the present study. As there were no large differences between the intervention groups, and the only difference was the information the participants received. Furthermore, the primary difference between our study and most placebo trials is the period of training, as most other placebo studies only investigate acute measures (Hurst, Schipof-Godart et al. 2020). In addition, our focus was on the training configuration of the program, not on a dietary supplement, as in other comparable trials. In previous investigations, 10-week training sessions resulted in greater strength improvements (ES > 0.50), but because the athletes in the present study were in competition season, lower results should be anticipated (Freitas, Martinez-Rodriguez et al. 2017, Bauer, Uebellacker et al. 2019).

5.2.7 Factors Affecting Placebo Responses in Training Interventions

Placebo (and nocebo) effects encompass a broad range of events that aren't confined to a direct response to a placebo (or nocebo) treatment (Beedie and Foad 2009). These effects can be brought about by a variety of factors that are not directly related to the treatment, such as the participant's expectations, previous experiences, the quality of the relationship between the participant and researcher, trust, empathy, and the overall procedures surrounding the administration of the intervention (Beedie and Foad 2009, Beedie, Benedetti et al. 2018, Hurst, Schipof-Godart et al. 2020). For example, it is possible that people in the placebo group have higher expectations of themselves (or perceive that the researchers have higher expectations of them) and, as a result, push their limitations somewhat further than those in the control group (Beedie and Foad 2009, Beedie, Benedetti et al. 2018, Hurst, Schipof-Godart et al. 2020). Those who have attempted to measure maximum sports performances, for instance, are aware that not all "max" efforts are maximal and indicative of capability. What does it imply when scientists say something like "subjects were verbally motivated and urged to provide their utmost effort?" Are we aware of the preconceived notions and expectations of the subjects? This view is consistent with the findings of the current investigation since only the one repetition maximum (1RM) squat revealed a significant group difference. In this test, the weight is increased depending on the judgment of both the participants and the researchers. On the other hand, the jumping test, the sprinting test, and the power test are somewhat less susceptible to subjective interpretation. It is interesting to note that although participants' subjective expectations could have influenced the outcomes of the test, the only group that increased their muscle thickness was the placebo group, while the control group did not. Indicating that there may be a component of the placebo effect independent of the testing situation.

The differences in participants' expectations towards the intervention are still another possible reason for the different training results that we detected. These expectations further predicted participants' adherence to the training program. Where greater self–reported expectations at the pretest resulted in more training sessions completed. At first glance, it could appear that sticking to the training program is an apparent explanation for the difference in the group's strength improvements, yet such an explanation is not complete. In the first place, adherence was not shown to be correlated with the strength improvements (r = -0.12), nor was it found to be a significant moderator in an ANCOVA analysis. As a result, the greater improvement in strength seen in the placebo group appears to be independent of the adherence shown in that group. This finding should not come as a surprise because more training does not necessarily result in better performance. This is especially true when one considers that the athletes who participated in this study were in the middle of their competitive season, which included numerous practices and matches (Figueiredo, de Salles et al. 2018).

A second likely reason for the strength improvement is that the placebo group had superior "quality" training than the control group (González-Badillo, Rodríguez-Rosell et al. 2014). It is well-established, for instance, that the intent to move weights with maximal intentional effort influences training adaptations (González-Badillo, Rodríguez-Rosell et al. 2014). Moreover, Jiménez-Alonso et al. (2010) demonstrate that different motivational strategies during resistance training affect exercise performance (i.e., effort/velocity of the movements) (Jiménez-Alonso, García-Ramos et al. 2020). Providing athletes with feedback during training, fostering inter-subject competitiveness, and providing vocal encouragement, among other tactics, also have been shown to induce a greater effort (or “quality”) in training. (Campenella, Mattacola et al. 2000, Jiménez-Alonso, García-Ramos et al. 2020, Nickerson, Williams et al. 2020). Hence, it is possible that the individuals in the placebo group carried out the exercise with a greater "quality" (i.e., effort), which had a further impact on the results of the training. In a similar vein, there is a possibility that people in the placebo group adjusted other behaviors as well, such as their sleeping or eating habits, or even engaged in greater physical activity. We were unable to observe and monitor the training sessions or lifestyle behaviors that may have validated or denied these predictions because of the practical limits and covid restrictions that we faced.

5.2.8 Individualized Training Based on Force-Velocity Profiling and the Placebo Effect

There were no statistically significant differences in any of the included measures evaluating the efficacy of the "individualized training," regardless of which group was assigned the placebo. As we have seen earlier in the discussion and from Study II, the effects reported after individualized training based on FV-profile have been mixed (Jiménez-Reyes, Samozino et al. 2017, Rakovic, Paulsen et al. 2018, Álvarez, García et al. 2019, Jiménez-Reyes, Samozino et al. 2019, Simpson, Waldron et al. 2020, Zabaloy, Pareja-Blanco et al. 2020, Lindberg, Solberg et al. 2021, Lindberg, Lohne-Seiler et al. 2022). In the first two studies on the topic, which were carried out by the people who came up with the concept, they discovered that the intervention had significant effect sizes, ranging from 0.7 to 1.0, while the control group showed no changes (ES: 0.14) (Jiménez-Reyes, Samozino et al. 2017, Jiménez-Reyes, Samozino et al. 2019). In one of the latter studies, with a positive effect, slightly lower effects were found with effect sizes of 0.37 vs. 0.12 for the intervention vs control group, respectively. Notably, as discussed earlier, according to the initial calculations that underpin the whole notion of training according to the FV profile, the findings from both investigations are 5-7 times bigger than what can be accounted for by the theoretical framework. In other words, even if one were to concede that it is possible to individualize training according to the FV profile, this does not mean that the theory alone can adequately explain the findings obtained in the past. Because both the researcher's and the participants' expectations of the intervention might have an impact on the findings of the study, the results of previous trials are possibly confounded by placebo effects. (Halson, Martin et al. 2013, Brown 2015, Holman, Head et al. 2015).

5.3 Methodological considerations

The studies included in the present thesis used different study designs, each with its own strengths and weaknesses, as well as other factors worth considering when interpreting the findings. These factors will be discussed in the following section.

Study I utilized an experimental approach with a longitudinal design using repeated measures of the participants. The study utilized a multicenter methodology to collect data from a large sample of male and female athletes from a variety of sporting backgrounds. By using a multicenter design, we could include a more significant number of participants, hence increasing the ecological validity of the results (Garcia-Ramos, Janicijevic et al. 2020). Ecological validity in this context refers to the extent to which the findings of a study can be generalized to real-world settings. The equipment and test leaders varied across the testing center but were constant within each participant. Not all test centers had the same equipment; hence, to make comparisons across methods, we conducted a separate analysis, including results from only one of the centers. That way, we got the benefit of both approaches in one study, one analysis of a smaller sample under identical conditions, and one large, aggregated sample under different test leaders, etc. The conclusions were then based on the more controlled sample and supported by the findings in the larger aggregated sample.

When it comes to specific protocol details, there are several methodological limitations that need to be considered. To begin, the disparity in the total number of loading conditions (i.e., 5 for vertical jumping and 10 for leg press) and the relative position on the FV-curve will invariably influence the agreement measures. In addition, the difference in push-off distance between the leg press, which is standardized to the vertical femur, and vertical jumping, which is standardized to the depth that the individual chooses, could influence the variation among these conditions (Janicijevic, Knezevic et al. 2019). It is also possible that the leg press protocol, which included pauses of 10–20 seconds for the light weights and 20–40 seconds for the heavy loads, caused some fatigue between repetitions and influenced the FV–relationship (García-Ramos, Torrejón et al. 2018). From the force plate method, the 5 SD threshold for determining the beginning of the movement will affect the average values of force and velocity and, consequently, the FV variables. This threshold is sensitive to minor movements and a source of uncontrolled error, especially in the SJ condition, but also in the CMJ condition (Pérez-Castilla, Rojas et al. 2019). In addition, for the agreement analysis, the force plate was sampled at 200 Hz as opposed to 1000 Hz before (Jiménez-Reyes, Samozino et al. 2017), which may have influenced the results. However, for the aggregated analysis of reliability, both 200 Hz and 2000 Hz force plates were utilized, and we would argue that the reliability findings are independent of sampling frequency. Another source of error worth discussing is the analysis procedure from the leg press software. For example, the cut-off threshold for the start and end of the contraction is set as a percentage point of 5% instead of, for example, the 5SD method used in the force plate method. This 5% cutoff will inevitably lead to larger absolute cutoff values for more extensive push ranges, for example, in taller subjects, or in lighter loads vs heavy where the push distances are longer. This analytical procedure is a source of error, although we have recently found these errors to be relatively small (Lindberg, Eythorsdottir et al. 2021). Regarding the encoder, an important consideration is that the calculation method used in our study is also specific to the software we used, for example, by including the flight phase and not calculating the acceleration and force from instantaneous values, which would be more theoretically correct. Hence, one cannot necessarily generalize our findings to other linear position transducers which use different approaches to calculate force (Garnacho-Castaño, López-Lastra et al. 2015). Further, the jumps in this study were done with free weights, making it difficult to standardize the jumps' center of mass using thigh depth or knee angle alone as a reference. These deviations in the center of mass are probably reduced when smith machines are utilized. These restrictions unavoidably impact both the test-retest reliability and the agreement among methodologies, as it is hard to determine which source of variability contributes to the observed outcomes in the study. However, the use of free weights enhances the ecological validity of the study, as this is a common practice among athletes.

In Study II, we utilized a multicenter, pre-post intervention design with participants allocated to different training groups based on their force-velocity (FV) profiles. Highly trained handball, soccer, and ice-hockey athletes took part in the study. During the training sessions, experienced coaches provided close supervision. Importantly, in the context of the placebo effect, all the subjects were presented with the training where all approaches were considered equally uncertain in their efficacy. As the study was designed where some subjects were training to either reduce or increase their optimal-force velocity profile, this was both the most practical way of presenting the project to the athletes, as well as a way of avoiding confounding the effects of placebos and nocebos. From practical experience, we already knew that it was hard to engage and get all the athletes to complete the scheduled training sessions if they were told they were in a control group or that they got less effective training than their peers. A similar observation is well documented in the literature (Hurst, Schipof-Godart et al. 2020), and we also found this effect in study III. Hence, we would argue that setting neutral expectations for the athletes in all three training groups was a big strength of the study design in study II. Further, regarding the multicenter study design, oppositely to Study I, the test leaders and equipment in Study II were constant across centers. Meaning that the test leaders traveled with the equipment to assess the athletes at all the centers. Unfortunately, most participants were classified as velocity dominant or well-balanced, resulting in an unequal distribution between groups. In addition, the stratified randomization to 3 distinct training programs resulted in an over-allocation of participants to the AW group. This disparate distribution decreased the statistical power relative to what was computed for one of the groups. Consequently, it is not possible to compare smaller subgroups, such as different training programs for individuals with different deficits. Due to the decreased statistical power, we employed three categories for FV-deficits as opposed to the five used in prior studies (Jiménez-Reyes, Samozino et al. 2017, Álvarez, García et al. 2019, Jiménez-Reyes, Samozino et al. 2019, Simpson, Waldron et al. 2020).

In Study III, we utilized a randomized controlled trial design with a placebo intervention and a control group. The methodology of this study has several advantages as well as some disadvantages. It takes a novel approach to investigate the placebo effect in training interventions, with the goal of determining whether subjects who are told they are in the intervention group achieve better training results compared to those who are in the control group. However, the study does have a few flaws, including a small sample size, which both raises the risk of making random errors and makes it more difficult to arrive at conclusive findings. In addition, the lack of stringent control over the training sessions and lifestyle habits of the participants could have influenced the results. Factors such as sleep, nutrition, or additional exercises performed outside the scope of the prescribed program could have played a role in the outcomes that were observed. Additionally, there was a lack of supervision and oversight during the training sessions, which may have contributed to varying levels of effort and quality of training among the participants, both of which may have influenced the results. Although the lack of control over the training sessions and lifestyle habits in the study can be viewed as a weakness, the increased ecological validity is a strength in this context. Meaning the study's lack of control over participants' training sessions and lifestyle habits better reflects a real-world scenario. In actual sports settings, athletes may not always have strict supervision or control over their daily habits. As such, the outcomes observed in the study are arguably more representative of the experiences of athletes in their natural environments, making the findings more generalizable and applicable to real-life situations. Additionally, the placebo effect is probably harder to detect under more strict conditions, as the expectations effect most likely influences a multitude of factors (Hurst, Schipof-Godart et al. 2020). Further, comparable to Study II, there are some weaknesses related to sample, size, and group allocation. There was a disparity in the distribution of participants throughout the spectrum of FV profiles since every participant was either classed as having a velocity-dominated profile or a well-balanced profile. Because of this, it is hard to compare more specific subgroups, such as various training programs designed to address a variety of weaknesses. It is important to note that such unequal distribution was observed in previous studies, and the current study was planned with that knowledge in mind. The primary analysis is conducted independently of the sub-groups (That is, Placebo and Control do, on average, the same kind of training). Most importantly, due to the relatively small sample size, the study should be considered a pilot study, where future full-powered trials should be conducted.

6 Conclusion

The Ph.D. thesis investigated the use of force-velocity (FV) profiling as a tool for performance assessment and individualized training prescriptions in athletes. Three experimental study designs were conducted to this end.

Study I primarily aimed to evaluate the reliability and agreement across the commonly utilized equipment for assessing force-velocity profiles. Despite the strong linearity observed for individual FV profiles, the slope of the force-velocity profile (S_{FV}) and theoretical maximal velocity (V_0) was found to have poor reliability in all methods assessed during vertical jumping. The findings indicated the need for efforts to either reduce variation in jumping performance or to assess loads closer to the FV-intercept. Theoretical maximal force (F_0) and power (P_{max}) demonstrated high reliability and good agreement across methods, reaffirming their utility in research and coaching. However, the poor reliability of V_0 and S_{FV} highlights the caution required in their assessment and interpretation.

In Study II, we tested the effectiveness of an individualized training approach based on FV profiling. We hypothesized that this method would enhance jump height compared to a traditional power training regimen. The intervention resulted in no significant group differences for any of the performance measures, challenging the efficacy of individualized training based on FV profiling. Changes towards the optimal squat jump (SJ) force-velocity profile were found to be negatively correlated with changes in SJ height, while changes in SJ power were positively related to changes in SJ height and countermovement jump (CMJ) height. These findings do not support the notion of individualizing training based on FV profiling but do underscore the need to shift the entire FV curve to the right, thus improving power across the entire force-velocity continuum.

In Study III, our main goal was to investigate the psychological impact of believing to be receiving optimized training as opposed to a generic program, examining its implications as a placebo effect. Despite undertaking identical training, those who were informed they were part of the intervention group manifested superior enhancement in their 1RM squat than the control group participants. This group also displayed a trend towards increased muscle thickness, which exhibited a strong correlation with the changes in leg strength. Such placebo effects were found to be on par with effects noted in previous sports science literature that implemented various placebo interventions. Interestingly, the frequency of adherence to the training program didn't account for the observed strength gain difference, suggesting the potential independence of the increased improvement in the placebo group from their training routine. However, we cannot discount the possibility that the placebo group experienced enhanced training “quality” or heightened motivation. Furthermore, the effectiveness of "individualized training" remained consistent, irrespective of the placebo group classification. Considering the potential placebo effects confounding previous studies, our results indicate the possibility that expectations of both researchers and participants may significantly influence the outcome of sports training interventions.

7 Perspective

The studies presented in this thesis contribute to our understanding of force-velocity profiling as a tool for performance assessment and individualized training in athletes. While there is still much to learn about this approach, the findings offer insights into the potential benefits and limitations of using force-velocity profiling in practice.

Firstly, Study I provides useful information for coaches and trainers regarding the appropriate equipment and methods to use when assessing force-velocity profiles. The study suggests that theoretical maximal force and power are the most reliable and accurate measures, while velocity and slope of the force-velocity profile are less reliable. Coaches and trainers should consider using equipment and methods that provide reliable and accurate measures when assessing their athletes' performance. However, it is important to be aware of the limitations of force-velocity profiling, especially when assessing jumping tasks. To improve the accuracy of force-velocity profile assessments, efforts should be made to reduce variation in jumping performance and/or assess loads closer to the force-velocity intercepts.

Secondly, the results of Study II challenge the notion of individualizing training based on FV profiling. The study did not find significant group differences in performance measures, which suggests that individualized training based on FV profiling may not be as effective as previously thought. However, the study highlights the importance of improving power across the entire force-velocity continuum by shifting the entire FV curve to the right. This finding provides practical guidance for coaches and trainers to focus on developing power across all loading conditions.

Finally, the findings from Study III suggest that the expectations of both researchers and participants may significantly influence the outcome of sports training interventions. The study's results indicate the possibility that placebo effects may confound the results of previous studies and that the expectations of both researchers and participants may significantly influence the outcome of sports training interventions. These findings underscore the need for caution when interpreting the results of sports training interventions and highlight the importance of considering the potential impact of placebo effects when designing and conducting such studies. Coaches and trainers can use this knowledge to create more effective training programs by considering the potential placebo effect. By creating a positive and motivating environment, coaches and trainers can help maximize the benefits of training and performance.

Considering the methodological limitations discussed, both concerning measurement accuracy and experimental design, future research on the topic should aim to address these issues. For example, by using biomechanical simulation models, one can rule out both the limitation of measurements and human expectations to look at the effect of different individualized training approaches. In the context of the placebo effect, future research should aim to investigate the psychological mechanisms that underlie the placebo effect in sports training interventions. Additionally, it is recommended that future studies try to control for the placebo effect as much as possible. As it is difficult to conduct double-blinded exercise interventions, there are several suggestions to minimize the potential impact of placebo effects on the study results. Researchers could use a control group that does a different exercise rather than no exercise. Pre- and post-study questionnaires can also measure participants' expectations to see if they differ between groups. Clear, balanced communication about the study's possible outcomes is also essential to prevent skewed expectations that can heighten placebo effects. By addressing these considerations in their design, future studies could produce more accurate, reliable, and generalizable results.

8 References

Alcazar, J., Cornejo-Daza, P. J., Sánchez-Valdepeñas, J., Alegre, L. M., & Pareja-Blanco, F. (2021). Dose–response relationship between velocity loss during resistance training and changes in the squat force–velocity relationship. *International journal of sports physiology and performance, 16*(12), 1736-1745.

Alcazar, J., Csapo, R., Ara, I., & Alegre, L. M. (2019). On the shape of the force-velocity relationship in skeletal muscles: the linear, the hyperbolic and the double-hyperbolic. *Frontiers in physiology, 10*, 769.

Alcazar, J., Navarro-Cruz, R., Rodriguez-Lopez, C., Vila-Maldonado, S., Ara, I., & Alegre, L. M. (2018). The double-hyperbolic force-velocity relationship in humans. *Acta Physiologica*.

Alcazar, J., Rodriguez-Lopez, C., Ara, I., Alfaro-Acha, A., Rodríguez-Gómez, I., Navarro-Cruz, R., . . . Alegre, L. M. (2018). Force-velocity profiling in older adults: An adequate tool for the management of functional trajectories with aging. *Experimental gerontology, 108*, 1-6.

Álvarez, J. A. E., García, J. P. F., Da Conceição, F. A., & Jiménez-Reyes, P. (2019). Individualized Training Based on Force–Velocity Profiling During Jumping in Ballet Dancers. *International journal of sports physiology and performance, 1*(aop), 1-7.

Ariel, G., & Saville, W. J. J. o. a. p. (1972). Effect of anabolic steroids on reflex components. *32*(6), 795-797.

Attia, A., Dhahbi, W., Chaouachi, A., Padulo, J., Wong, D., & Chamari, K. (2017). Measurement errors when estimating the vertical jump height with flight time using photocell devices: the example of Optojump. *Biology of sport, 34*(1), 63-70.

Baena-Raya, A., García-Mateo, P., García-Ramos, A., Rodríguez-Pérez, M. A., & Soriano-Maldonado, A. (2022). Delineating the potential of the vertical and horizontal force-velocity profile for optimizing sport performance: A systematic review. *Journal of sports sciences, 40*(3), 331-344.

Bauer, P., Uebellacker, F., Mitter, B., Aigner, A. J., Hasenoehrl, T., Ristl, R., . . . sport, m. i. (2019). Combining higher-load and lower-load resistance training exercises: a systematic review and meta-analysis of findings from complex training studies. *22*(7), 838-851.

Beedie, C., Benedetti, F., Barbiani, D., Camerone, E., Cohen, E., Coleman, D., . . . Foad, A. (2018a). Consensus statement on placebo effects in sports and exercise: The need for conceptual clarity, methodological rigour, and the elucidation of neurobiological mechanisms. *European Journal of Sport Science, 18*(10), 1383-1389.

Beedie, C. J., & Foad, A. J. J. S. M. (2009). The placebo effect in sports performance. *39*(4), 313-329.

Biewener, A. A., Farley, C. T., Roberts, T. J., & Temaner, M. (2004). Muscle mechanical advantage of human walking and running: implications for energy cost. *Journal of Applied Physiology, 97*(6), 2266-2274.

Biewener, A. A., & Roberts, T. J. (2000). Muscle and tendon contributions to force, work, and elastic energy savings: a comparative perspective. *Exerc Sport Sci Rev, 28*(3), 99-107.

Bobbert, M. F. (2012). Why is the force-velocity relationship in leg press tasks quasi-linear rather than hyperbolic? *Journal of Applied Physiology, 112*(12), 1975-1983.

Bobbert, M. F., Lindberg, K., Bjørnsen, T., Solberg, P., & Paulsen, G. (2023). The Force-Velocity Profile for Jumping: What it Is and What it Is Not. *Medicine & Science in Sports & Exercise*, 10.1249.

Bosco, C., Ito, A., KOMI, P. V., LUHTANEN, P., RAHKILA, P., RUSKO, H., & VIITASALO, J. T. (1982). Neuromuscular function and mechanical efficiency of human leg extensor muscles during jumping exercises. *Acta Physiologica Scandinavica, 114*(4), 543-550. doi:https://doi.org/10.1111/j.1748-1716.1982.tb07022.x

Brown, W. A. J. R. I. m. j. (2015). Expectation, the placebo effect and the response to treatment. *98*(5), 19.

Campenella, B., Mattacola, C. G., Kimura, I. F. J. I., & science, e. (2000). Effect of visual feedback and verbal encouragement on concentric quadriceps and hamstrings peak torque of males and females. *8*(1), 1-6.

Chang, Y.-W., Su, F.-C., Wu, H.-W., & An, K.-N. (1999). Optimum length of muscle contraction. *Clinical Biomechanics, 14*(8), 537-542.

Cormie, P., McBride, J. M., & McCaulley, G. O. (2009). Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *The Journal of Strength Conditioning Research, 23*(1), 177-186.

Cormie, P., McCaulley, G. O., & McBride, J. M. (2007). Power versus strength-power jump squat training: influence on the load-power relationship. *39*(6), 996-1003.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Adaptations in athletic performance after ballistic power versus strength training. *Medicine, Science in Sports Exercise, 42*(8), 1582-1598.

Crewther, B., Cronin, J., & Keogh, J. (2005). Possible stimuli for strength and power adaptation. *Sports medicine, 35*(11), 967-989.

Cuk, I., Markovic, M., Nedeljkovic, A., Ugarkovic, D., Kukolj, M., & Jaric, S. (2014). Force–velocity relationship of leg extensors obtained from loaded and unloaded vertical jumps. *European Journal of Applied Physiology, 114*(8), 1703-1714.

Dorel, S. (2018). Maximal force-velocity and power-velocity characteristics in cycling: Assessment and relevance. In *Biomechanics of training and testing* (pp. 7-31): Springer.

Driss, T., Vandewalle, H., & Monod, H. (1998). Maximal power and force-velocity relationships during cycling and cranking exercises in volleyball players. Correlation with the vertical jump test. *The Journal of sports medicine and physical fitness, 38*(4), 286-293. Retrieved from http://europepmc.org/abstract/MED/9973770

Duchateau, J., & Enoka, R. M. (2008). Neural control of shortening and lengthening contractions: influence of task constraints. *The Journal of physiology, 586*(24), 5853-5864.

Edman, K. (1976). Mulieri LA, Scubon-Mulieri B. *Non-hyperbolic force-velocity relationship in single muscle fibres. Acta Physiol Scand, 98*, 143-156.

Feeney, D., Stanhope, S. J., Kaminski, T. W., Machi, A., & Jaric, S. (2016a). Loaded vertical jumping: force–velocity relationship, work, and power. *Journal of applied biomechanics, 32*(2), 120-127.

Fessl, I., Wiesinger, H.-P., Kröll, J. J. I. J. o. S. P., & Performance. (2022). Power–Force–Velocity Profiling as a Function of Used Loads and Task Experience. *1*(aop), 1-7.

Figueiredo, V. C., de Salles, B. F., & Trajano, G. S. J. S. M. (2018). Volume for muscle hypertrophy and health outcomes: the most effective variable in resistance training. *48*(3), 499-505.

Freitas, T. T., Martinez-Rodriguez, A., Calleja-González, J., & Alcaraz, P. E. J. P. o. (2017). Short-term adaptations following complex training in team-sports: A meta-analysis. *12*(6), e0180223.

Freund, H.-J. (1983). Motor unit and muscle activity in voluntary motor control. *Physiological Reviews, 63*(2), 387-436.

Frost, D. M., Cronin, J., & Newton, R. U. (2010). A biomechanical evaluation of resistance. *Sports medicine, 40*(4), 303-326.

Fulton, J. F., & Cushing, H. (1936). A bibliographical study of the Galvani and the Aldini writings on animal electricity. *Annals of Science, 1*(3), 239-268.

García-Ramos, A., Feriche, B., Pérez-Castilla, A., Padial, P., & Jaric, S. (2017). Assessment of leg muscles mechanical capacities: Which jump, loading, and variable type provide the most reliable outcomes? *European journal of sport science, 17*(6), 690-698.

Garcia-Ramos, A., Janicijevic, D. J. I., & Science, E. (2020). Potential benefits of multicenter reliability studies in sports science: A practical guide for its implementation. (Preprint), 1-6.

García-Ramos, A., Jaric, S., Pérez-Castilla, A., Padial, P., & Feriche, B. (2017). Reliability and magnitude of mechanical variables assessed from unconstrained and constrained loaded countermovement jumps. *Sports Biomechanics, 16*(4), 514-526. doi:10.1080/14763141.2016.1246598

García-Ramos, A., Pérez-Castilla, A., & Jaric, S. (2018). Optimisation of applied loads when using the two-point method for assessing the force-velocity relationship during vertical jumps. *Sports Biomechanics*, 1-16.

García-Ramos, A., Pérez-Castilla, A., Morales-Artacho, A. J., Almeida, F., Padial, P., Bonitch-Góngora, J., . . . Feriche, B. (2019). Force-velocity relationship in the countermovement jump exercise assessed by different measurement methods. *Journal of human kinetics*.

García-Ramos, A., Torrejón, A., Feriche, B., Morales-Artacho, A. J., Pérez-Castilla, A., Padial, P., & Jaric, S. (2018). Selective effects of different fatigue protocols on the function of upper body muscles assessed through the force–velocity relationship. *European Journal of Applied Physiology, 118*, 439-447.

Garnacho-Castaño, M. V., López-Lastra, S., & Maté-Muñoz, J. L. (2015). Reliability and Validity Assessment of a Linear Position Transducer. *Journal of Sports Science & Medicine, 14*(1), 128-136. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4306764/

Gasser, H. S., & Hill, A. V. (1924). The dynamics of muscular contraction. *Proceedings of the Royal Society of London. Series B, containing papers of a biological character, 96*(678), 398-437.

Giroux, C., Rabita, G., Chollet, D., & Guilhem, G. (2015). What is the best method for assessing lower limb force-velocity relationship? *International journal of sports medicine, 36*(02), 143-149.

Gittoes, M. J. R., & Wilson, C. (2010). Intralimb Joint Coordination Patterns of the Lower Extremity in Maximal Velocity Phase Sprint Running. *Journal of applied biomechanics, 26*(2), 188-195. doi:10.1123/jab.26.2.188

González-Badillo, J. J., Rodríguez-Rosell, D., Sánchez-Medina, L., Gorostiaga, E. M., & Pareja-Blanco, F. J. E. j. o. s. s. (2014). Maximal intended velocity training induces greater gains in bench press performance than deliberately slower half-velocity training. *14*(8), 772-781.

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), 1-16.

Gu, A. P., Gu, C. N., Ahmed, A. T., Murad, M. H., Wang, Z., Kallmes, D. F., & Brinjikji, W. J. J. o. c. e. (2017). Sham surgical procedures for pain intervention result in significant improvements in pain: systematic review and meta-analysis. *83*, 18-23.

Gülch, R. (1994). Force-velocity relations in human skeletal muscle. *International journal of sports medicine, 15*(S 1), S2-S10.

Hackett, D., Davies, T., Soomro, N., & Halaki, M. (2016). Olympic weightlifting training improves vertical jump height in sportspeople: a systematic review with meta-analysis. *Br J Sports Med, 50*(14), 865-872.

Halliday, D., Resnick, R., & Walker, J. (2013). *Fundamentals of physics*: John Wiley & Sons.

Halson, S. L., Martin, D. T. J. I. j. o. s. p., & performance. (2013). Lying to win—placebos and sport science. *8*(6), 597-599.

Harris, N. K., Cronin, J. B., Hopkins, W. G., & Hansen, K. T. (2008). Relationship between sprint times and the strength/power outputs of a machine squat jump. *The Journal of Strength Conditioning Research, 22*(3), 691-698.

Haugen, T. A., Breitschädel, F., Wiig, H., Seiler, S. J. I. J. o. S. P., & Performance. (2020). Countermovement Jump Height in National-Team Athletes of Various Sports: A Framework for Practitioners and Scientists. *1*(aop), 1-6.

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 Conditioning Journal, 38*(4), 42.

Herzog, W. (2014). Mechanisms of enhanced force production in lengthening (eccentric) muscle contractions. *Journal of Applied Physiology, 116*(11), 1407-1417.

Hill, A. V. (1922). The maximum work and mechanical efficiency of human muscles, and their most economical speed. *The Journal of physiology, 56*(1-2), 19.

Hill, A. V. (1938). The heat of shortening and the dynamic constants of muscle. *Proceedings of the Royal Society of London. Series B-Biological Sciences, 126*(843), 136-195.

Hill, A. V. (1955). The influence of the external medium on the internal pH of muscle. *Proceedings of the Royal Society of London. Series B-Biological Sciences, 144*(914), 1-22.

Hill, A. V. (1964). The effect of load on the heat of shortening of muscle. *Proceedings of the Royal Society of London. Series B. Biological sciences, 159*(975), 297-318.

Hitchcock-DeGregori, S. E., & Irving, T. C. (2014). Hugh E. Huxley: the compleat biophysicist. *Biophysical journal, 107*(7), 1493-1501.

Holman, L., Head, M. L., Lanfear, R., & Jennions, M. D. J. P. b. (2015). Evidence of experimental bias in the life sciences: why we need blind data recording. *13*(7), e1002190.

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports medicine, 30*(1), 1-15.

Hopkins, W. G. (2017). Spreadsheets for analysis of validity and reliability. *Sportscience, 21*.

Hopkins, W. G., Schabort, E. J., & Hawley, J. A. (2001). Reliability of power in physical performance tests. *Sports Med, 31*(3), 211-234.

Hughes, L. J., Peiffer, J. J., & Scott, B. R. (2020). Load–velocity relationship 1RM predictions: A comparison of Smith machine and free-weight exercise. *Journal of sports sciences, 38*(22), 2562-2568.

Hurst, P., Foad, A., Coleman, D., Beedie, C. J. M., Sports, S. i., & Exercise. (2017). Athletes intending to use sports supplements are more likely to respond to a placebo.

Hurst, P., Schipof-Godart, L., Szabo, A., Raglin, J., Hettinga, F., Roelands, B., . . . Beedie, C. J. E. j. o. s. s. (2020). The Placebo and Nocebo effect on sports performance: A systematic review. *20*(3), 279-292.

Huxley, H., & Hanson, J. (1954). Changes in the cross-striations of muscle during contraction and stretch and their structural interpretation. *Nature, 173*(4412), 973-976.

Janicijevic, D., Knezevic, O. M., Mirkov, D. M., Pérez-Castilla, A., Petrovic, M., Samozino, P., & Garcia-Ramos, A. (2019). Assessment of the force-velocity relationship during vertical jumps: influence of the starting position, analysis procedures and number of loads. *European Journal of Sport Science*, 1-10.

Janicijevic, D. N., Knezevic, O. M., Mirkov, D. M., Pérez-Castilla, A., Petrovic, M. R., & García-Ramos, A. (2019). Magnitude and reliability of mechanical outputs obtained during loaded squat jumps performed from different knee angles. *Sports Biomechanics*, 1-13.

Jaric, S. (2015). Force-velocity relationship of muscles performing multi-joint maximum performance tasks. *International journal of sports medicine, 36*(09), 699-704.

Jiménez-Alonso, A., García-Ramos, A., Cepero, M., Miras-Moreno, S., Rojas, F. J., Pérez-Castilla, A. J. J. o. s., & research, c. (2020). Effect of Augmented Feedback on Velocity Performance During Strength-Oriented and Power-Oriented Resistance Training Sessions.

Jimenez-Reyes, P., Samozino, P., Brughelli, M., & Morin, J. B. (2016). Effectiveness of an Individualized Training Based on Force-Velocity Profiling during Jumping. *Front Physiol, 7*, 677. doi:10.3389/fphys.2016.00677

Jiménez-Reyes, P., Samozino, P., & Morin, J.-B. (2019). Optimized training for jumping performance using the force-velocity imbalance: Individual adaptation kinetics. *PLoS One, 14*(5).

Jiménez-Reyes, P., Samozino, P., Pareja-Blanco, F., Conceição, F., Cuadrado-Peñafiel, V., González-Badillo, J., & Morin, J.-B. (2017). Validity of a simple method for measuring force-velocity-power profile in countermovement jump. *International journal of sports physiology and performance, 12*(1), 36-43.

Kallenberg, L. A., & Hermens, H. J. (2008). Behaviour of a surface EMG based measure for motor control: Motor unit action potential rate in relation to force and muscle fatigue. *Journal of Electromyography and Kinesiology, 18*(5), 780-788.

Kaneko, M., Fuchimoto, T., Toji, H., & Suei, K. (1983). Training effect of different loads on the force-velocity relationship and mechanical power output in human muscle. *Scand J Sports Sci, 5*(2), 50-55.

Kaptchuk, T. J., Goldman, P., Stone, D. A., & Stason, W. B. J. J. o. c. e. (2000). Do medical devices have enhanced placebo effects? *, 53*(8), 786-792.

Keiser. *Keiser A420 Operations and Maintenance Manual Rev X.* Retrieved from http://manuals.keiser.com/Software/A420/A420%20Manual%20Rev%20X.pdf

Knudson, D. V. (2009). Correcting the use of the term "power" in the strength and conditioning literature. *J Strength Cond Res, 23*(6), 1902-1908. doi:10.1519/JSC.0b013e3181b7f5e5

Kotani, Y., Haff, G. G., Nosaka, K., Guppy, S., Poon, W., Hori, G., . . . Research, C. (2021). Reliability of the squat jump force-velocity and load-velocity profiles.

Lake, J. P., Lauder, M. A., & Smith, N. A. (2012). Barbell kinematics should not be used to estimate power output applied to the barbell-and-body system center of mass during lower-body resistance exercise. *The Journal of Strength Conditioning Research, 26*(5), 1302-1307.

Larsen, F., Loturco, I., Sigvaldsen, E., Strand, M. F., & Magne, J. Reliability and validity of different lower-limb strength tests to determine 1RM in the Keiser A300 leg press.

Lesinski, M., Prieske, O., & Granacher, U. (2016). Effects and dose–response relationships of resistance training on physical performance in youth athletes: a systematic review and meta-analysis. *British journal of sports medicine, 50*(13), 781-795.

Levin, A., & Wyman, J. (1927). The viscous elastic properties of muscle. *Proceedings of the Royal Society of London. Series B, containing papers of a biological character, 101*(709), 218-243.

Lieber, R. L., & Fridén, J. (2000). Functional and clinical significance of skeletal muscle architecture. *Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine, 23*(11), 1647-1666.

Lindberg, Solberg, P., Rønnestad, B. R., Frank, M. T., Larsen, T., Abusdal, G., . . . Sports, S. i. (2021). Should we individualize training based on force-velocity profiling to improve physical performance in athletes?

Lindberg, K., Eythorsdottir, I., Solberg, P., Gløersen, Ø., Seynnes, O., Bjørnsen, T., . . . Performance. (2021). Validity of Force–Velocity Profiling Assessed With a Pneumatic Leg Press Device. *16*(12), 1777-1785.

Lindberg, K., Lohne-Seiler, H., Fosstveit, S. H., Sibayan, E. E., Fjeller, J. S., Løvold, S., . . . Sports, S. i. (2022). The effectiveness of Individualized training based on force-velocity profiling on physical function in older men.

Lindberg, K., Solberg, P., Bjørnsen, T., Helland, C., Rønnestad, B., Thorsen Frank, M., . . . Midttun, M. (2021). Force-velocity profiling in athletes: Reliability and agreement across methods. *PLoS One, 16*(2), e0245791.

Loturco, I., McGuigan, M., Freitas, T. T., Valenzuela, P., Pereira, L. A., & Pareja-Blanco, F. J. B. o. S. (2021). Performance and reference data in the jump squat at different relative loads in elite sprinters, rugby players, and soccer players. *38*(2), 219-227.

Maganaris, C. N., Collins, D., & Sharp, M. J. T. S. P. (2000). Expectancy effects and strength training: do steroids make a difference? *, 14*(3), 272-278.

Mangine, G. T., Gonzalez, A. M., Townsend, J. R., Wells, A. J., Beyer, K. S., Miramonti, A. A., . . . Hoffman, J. R. (2018). Influence of baseline muscle strength and size measures on training adaptations in resistance-trained men. *International journal of exercise science, 11*(4), 198.

Marcote-Pequeño, R., García-Ramos, A., Cuadrado-Peñafiel, V., González-Hernández, J. M., Gómez, M. Á., & Jiménez-Reyes, P. (2019). Association between the force–velocity profile and performance variables obtained in jumping and sprinting in elite female soccer players. *International journal of sports physiology and performance, 14*(2), 209-215.

Markovic, G. (2007). Does plyometric training improve vertical jump height? A meta-analytical review. *British journal of sports medicine, 41*(6), 349-355.

McBurnie, A. J., Allen, K. P., Garry, M., Martin, M., Jones, P. A., Comfort, P., & McMahon, J. J. (2019). The benefits and limitations of predicting one repetition maximum using the load-velocity relationship. *Strength & Conditioning Journal, 41*(6), 28-40.

McQuay, H., & Moore, R. J. P. M. J. (2005). Placebo. *81*(953), 155-160.

Meylan, C. M., Cronin, J. B., Oliver, J. L., Hughes, M. M., Jidovtseff, B., & Pinder, S. (2015a). The reliability of isoinertial force–velocity–power profiling and maximal strength assessment in youth. *Sports biomechanics, 14*(1), 68-80.

Meylan, C. M., Cronin, J. B., Oliver, J. L., Hughes, M. M., Jidovtseff, B., & Pinder, S. J. S. b. (2015b). The reliability of isoinertial force–velocity–power profiling and maximal strength assessment in youth. *14*(1), 68-80.

Mitchell, L. J., Argus, C. K., Taylor, K.-L., Sheppard, J. M., & Chapman, D. W. (2017). The effect of initial knee angle on concentric-only squat jump performance. *Research quarterly for exercise sport, Education and Society, 88*(2), 184-192.

Morales-Artacho, A. J., Ramos, A. G., Pérez-Castilla, A., Padial, P., Argüelles-Cienfuegos, J., de la Fuente, B., & Feriche, B. (2018). Associations of the Force-velocity Profile with Isometric Strength and Neuromuscular Factors. *International journal of sports medicine, 39*(13), 984-994.

Morin, J.-B., Jiménez-Reyes, P., Brughelli, M., & Samozino, P. J. S. M. (2019). When jump height is not a good indicator of lower limb maximal power output: theoretical demonstration, experimental evidence and practical solutions. *49*(7), 999-1006.

Morin, J.-B., & Samozino, P. (2018). *Biomechanics of training and testing: innovative concepts and simple field methods*: Springer.

Morin, J. B., & Samozino, P. (2016). Interpreting Power-Force-Velocity Profiles for Individualized and Specific Training. *Int J Sports Physiol Perform, 11*(2), 267-272. doi:10.1123/ijspp.2015-0638

Morris, C. G., Weber, J. A., & Netto, K. J. (2020). Relationship Between Mechanical Effectiveness in Sprint Running and Force-Velocity Characteristics of a Countermovement Jump in Australian Rules Football Athletes. *The Journal of Strength Conditioning Research*.

Moss, B., Refsnes, P., Abildgaard, A., Nicolaysen, K., & Jensen, J. (1997). Effects of maximal effort strength training with different loads on dynamic strength, cross-sectional area, load-power and load-velocity relationships. *European journal of applied physiology occupational physiology, 75*(3), 193-199.

Nickerson, B. S., Williams, T. D., Snarr, R. L., Garza, J. M., Salinas, G. J. T. J. o. S., & Research, C. (2020). Evaluation of load-velocity relationships and repetitions-to-failure equations in the presence of male and female spotters. *34*(9), 2427-2433.

Nuzzo, J. L., Anning, J. H., & Scharfenberg, J. M. (2011). The Reliability of Three Devices Used for Measuring Vertical Jump Height. *The Journal of Strength & Conditioning Research, 25*(9). Retrieved from https://journals.lww.com/nsca-jscr/Fulltext/2011/09000/The_Reliability_of_Three_Devices_Used_for.30.aspx

Nysether, S., Hopkins, W. G., Mentzoni, F., Paulsen, G., Haugen, T. A., & Solberg, P. A. (2023). Monitoring Changes in Lower-Limb Strength and Power in Elite Athletes With the Countermovement-Jump and Keiser Leg-Press Tests. *International journal of sports physiology and performance, 1*(aop), 1-7.

Padulo, J., Migliaccio, G. M., Ardigò, L. P., Leban, B., Cosso, M., & Samozino, P. (2017). Lower limb force, velocity, power capabilities during leg press and squat movements. *International journal of sports medicine, 38*(14), 1083-1089.

Pérez-Castilla, A., Rojas, F. J., & García-Ramos, A. (2019a). Assessment of unloaded and loaded squat jump performance with a force platform: Which jump starting threshold provides more reliable outcomes? *Journal of biomechanics, 92*, 19-28.

Pérez-Castilla, A., Rojas, F. J., & García-Ramos, A. J. S. B. (2019b). Reliability and magnitude of loaded countermovement jump performance variables: A technical examination of the jump threshold initiation. 1-15.

Rakovic, E., Paulsen, G., Helland, C., Eriksrud, O., & Haugen, T. (2018). The effect of individualised sprint training in elite female team sport athletes: A pilot study. *Journal of sports sciences, 36*(24), 2802-2808.

Rivière, J., Morin, J.-B., & Bowen, M. (2021). Exploring the velocity end of the force-velocity relationship in acyclic lower limb extensions.

Roberts, T. J. (2002). The integrated function of muscles and tendons during locomotion. *Comp Biochem Physiol A Mol Integr Physiol, 133*(4), 1087-1099. doi:10.1016/s1095-6433(02)00244-1

Samozino, Edouard, P., Sangnier, S., Brughelli, M., Gimenez, P., & Morin, J.-B. (2014). Force-velocity profile: imbalance determination and effect on lower limb ballistic performance. *International journal of sports medicine, 35*(06), 505-510.

Samozino, P. (2018). A Simple Method for Measuring Lower Limb Force, Velocity and Power Capabilities During Jumping. In J.-B. Morin & P. Samozino (Eds.), *Biomechanics of Training and Testing: Innovative Concepts and Simple Field Methods* (pp. 65-96). Cham: Springer International Publishing.

Samozino, P., Di Prampero, P. E., Belli, A., & Morin, J. B. (2012). Optimal force-velocity profile in ballistic movements--altius: citius or fortius? *Med Sci Sports Exerc, 44*(2), 313-322. doi:10.1249/MSS.0b013e31822d757a

Samozino, P., Edouard, P., Sangnier, S., Brughelli, M., Gimenez, P., & Morin, J.-B. (2014). Force-velocity profile: imbalance determination and effect on lower limb ballistic performance. *International journal of sports medicine, 35*(06), 505-510.

Samozino, P., Morin, J.-B., Hintzy, F., & Belli, A. (2010). Jumping ability: a theoretical integrative approach. *Journal of Theoretical Biology, 264*(1), 11-18.

Samozino, P., Rivière, J. R., Jimenez-Reyes, P., Cross, M. R., & Morin, J.-B. (2022). Is the Concept, Method, or Measurement to Blame for Testing Error? An Illustration Using the Force-Velocity-Power Profile.

International journal of sports physiology and performance, 17(12), 1760-1768.

Šarabon, N., Kozinc, Ž., & Marković, G. (2020). Force–velocity profile during vertical jump cannot be assessed using only bodyweight jump and isometric maximal voluntary contraction tasks. *Scientific reports, 10*(1), 1-12.

Šarabon, N., Kozinc, Ž., Ramos, A. G., Knežević, O. M., Čoh, M., & Mirkov, D. M. (2021). Reliability of Sprint Force-Velocity-Power Profiles Obtained with KiSprint System. *Journal of Sports Science Medicine, 20*(2), 357-364.

Shmueli, G. J. S. s. (2010). To explain or to predict? *, 25*(3), 289-310.

Simpson, A., Waldron, M., Cushion, E., & Tallent, J. (2020). Optimised force-velocity training during pre-season enhances physical performance in professional rugby league players. *Journal of sports sciences*, 1-10.

Sleivert, G., & Taingahue, M. (2004). The relationship between maximal jump-squat power and sprint acceleration in athletes. *European Journal of Applied Physiology, 91*(1), 46-52.

Slimani, M., Paravlic, A., & Granacher, U. (2018). A meta-analysis to determine strength training related dose-response relationships for lower-limb muscle power development in young athletes. *Frontiers in physiology, 9*, 1155.

Stojanović, E., Ristić, V., McMaster, D. T., & Milanović, Z. (2017). Effect of plyometric training on vertical jump performance in female athletes: a systematic review and meta-analysis. *Sports medicine, 47*(5), 975-986.

Suchomel, T. J., Nimphius, S., Bellon, C. R., & Stone, M. H. (2018). The importance of muscular strength: training considerations. *Sports medicine, 48*, 765-785.

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The importance of muscular strength in athletic performance. *Sports medicine, 46*, 1419-1449.

Sugi, H., & Chaen, S. (2016). Force-Velocity Relation: Its Implications about Molecular Mechanism of Muscle Contraction. *J Nanomed Nanotechnol, 7*(401), 2.

Sugi, H., & Ohno, T. (2019). Physiological significance of the force-velocity relation in skeletal muscle and muscle fibers. *International Journal of Molecular Sciences, 20*(12), 3075.

Ter Keurs, H., Iwazumi, T., & Pollack, G. (1978). The sarcomere length-tension relation in skeletal muscle. *The Journal of General Physiology, 72*(4), 565-592.

Thompson, S. W., Rogerson, D., Ruddock, A., Greig, L., Dorrell, H. F., & Barnes, A. (2021). A novel approach to 1RM prediction using the load-velocity profile: a comparison of models. *Sports, 9*(7), 88.

Thorstensson, A., Grimby, G., & Karlsson, J. (1976). Force-velocity relations and fiber composition in human knee extensor muscles. *Journal of Applied Physiology, 40*(1), 12-16.

Toji, H., & Kaneko, M. (2004). Effect of multiple-load training on the force-velocity relationship. *Journal of strength conditioning research, 18*(4), 792-795.

Toji, H., Suei, K., & Kaneko, M. (1997). Effects of combined training loads on relations among force, velocity, and power development. *Canadian Journal of Applied Physiology, 22*(4), 328-336.

Valenzuela, P. L., Sánchez-Martínez, G., Torrontegi, E., Vázquez-Carrión, J., Montalvo, Z., & Haff, G. G. (2021). Should We Base Training Prescription on the Force–Velocity Profile? Exploratory Study of Its Between-Day Reliability and Differences Between Methods. *International journal of sports physiology performance, 1*(aop), 1-7.

Van Den Tillaar, R., Ettema, G. J. J. o. s. s., & medicine. (2004). A force-velocity relationship and coordination patterns in overarm throwing. *3*(4), 211.

Vescovi, J. D., & McGuigan, M. R. (2008). Relationships between sprinting, agility, and jump ability in female athletes. *J Sports Sci, 26*(1), 97-107. doi:10.1080/02640410701348644

Wade, L., Lichtwark, G., & Farris, D. J. J. S. r. (2018). Movement strategies for countermovement jumping are potentially influenced by elastic energy stored and released from tendons. *8*(1), 1-11.

Westing, S., Seger, J., & Thorstensson, A. (1990). Effects of electrical stimulation on eccentric and concentric torque-velocity relationships during knee extension in man. *Acta Physiologica Scandinavica, 140*(1), 17-22.

Wickiewicz, T. L., Roy, R. R., Powell, P. L., Perrine, J. J., & Edgerton, V. R. (1984). Muscle architecture and force-velocity relationships in humans. *Journal of Applied Physiology, 57*(2), 435-443.

Williams, K. J., Chapman, D. W., Phillips, E. J., & Ball, N. (2018a). Effects of Athlete-Dependent Traits on Joint and System Countermovement-Jump Power. *International journal of sports physiology performance, 13*(10), 1378-1385.

Williams, K. J., Chapman, D. W., Phillips, E. J., & Ball, N. B. (2018c). Load-power relationship during a countermovement jump: A joint level analysis. *The Journal of Strength Conditioning Research, 32*(4), 955-961.

Williams, K. J., Chapman, D. W., Phillips, E. J., & Ball, N. B. (2019). Measurement bias in estimates of system power during a vertical jump. *Sports Biomechanics*, 1-13.

Winter, D. A. (2009). *Biomechanics and motor control of human movement*: John Wiley & Sons.

Xu, J., Zhang, Z., Zhao, J., Meyers, C. A., Lee, S., Qin, Q., & James, A. W. (2022). Interaction between the nervous and skeletal systems. *Frontiers in Cell and Developmental Biology, 10*, 976736.

Younger, J., Gandhi, V., Hubbard, E., & Mackey, S. J. C. T. (2012). Development of the Stanford Expectations of Treatment Scale (SETS): a tool for measuring patient outcome expectancy in clinical trials. *9*(6), 767-776.

Zabaloy, S., Pareja-Blanco, F., Giráldez, J. C., Rasmussen, J. I., González, J. G. J. I., & Science, E. (2020). Effects of individualized training programs based on the force-velocity imbalance on physical performance in rugby players. (Preprint), 1-10.

Zivkovic, M. Z., Djuric, S., Cuk, I., Suzovic, D., & Jaric, S. (2017). Muscle force-velocity relationships observed in four different functional tests. *Journal of human kinetics, 56*(1), 39-49.

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002a). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of Applied Physiology, 93*(4), 1318-1326.

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen (2002b). Neural adaptation to resistance training: changes in evoked V-wave and H-reflex responses. *Journal of Applied Physiology, 92*(6), 2309-2318.

Paper I

Force-velocity profiling in athletes: Reliability and agreement across methods

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RESEARCH ARTICLE

Force-velocity profiling in athletes: Reliability and agreement across methods

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Abstract

The aim of the study was to examine the test-retest reliability and agreement across methods for assessing individual force-velocity (FV) profiles of the lower limbs in athletes. Using a multicenter approach, 27 male athletes completed all measurements for the main analysis, with up to 82 male and female athletes on some measurements. The athletes were tested twice before and twice after a 2- to 6-month period of regular training and sport participation. The double testing sessions were separated by ~1 week. Individual FV-profiles were acquired from incremental loading protocols in squat jump (SJ), countermovement jump (CMJ) and leg press. A force plate, linear encoder and a flight time calculation method were used for measuring force and velocity during SJ and CMJ. A linear regression was fitted to the average force and velocity values for each individual test to extrapolate the FV-variables: theoretical maximal force (F_0), velocity (V_0), power (P_{max}), and the slope of the FV-profile (S_{FV}). Despite strong linearity (R^2>0.95) for individual FV-profiles, the S_{FV} was unreliable for all measurement methods assessed during vertical jumping (coefficient of variation (CV): 14–30%, interclass correlation coefficient (ICC): 0.36–0.79). Only the leg press exercise, of the four FV-variables, showed acceptable reliability (CV:3.7–8.3%, ICC:0.82–0.98). The agreement across methods for F_0 and P_{max} ranged from (Pearson r): 0.56–0.95, standard error of estimate (SEE%): 5.8–18.8, and for V_0 and S_{FV} r: -0.39–0.78, SEE%: 12.2–37.2. With a typical error of 1.5 cm (5–10% CV) in jump height, S_{FV} and V_0 cannot be accurately obtained, regardless of the measurement method, using a loading range corresponding to 40–70% of F_0. Efforts should be made to either reduce the variation in jumping performance or to assess loads closer to the FV-intercepts. Coaches and researchers should be aware of the poor reliability of the FV-variables obtained from vertical jumping, and of the differences across measurement methods.

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Introduction

Within strength and power training, force-velocity (FV) profiling has received increasing attention as a means to monitor training adaptations [1–3] and to serve as a basis for individual training prescriptions for athletes [3–6]. The concept of FV-profiling is based on the fundamental properties of skeletal muscles, where there is an inverse relationship between force and velocity [7].

In multi-joint movements, the FV-relationship is commonly described as linear [8], in contrast to the hyperbolic relationship observed in isolated muscles or single-joint movements [7]. In practice, athletes can perform maximal efforts against different loads while force and velocity are measured during vertical jumping or similar multi-joint movements. Based on such data, one can draw a linear regression line and extrapolate the theoretical maximal force (F_0) (i.e., force at zero velocity) and velocity (V_0) (i.e., velocity at zero force). Following that, the theoretical maximal power (P_{max}) can be calculated as ($F_0 \cdot V_0$)/4 and the slope of the FV-profile (S_{FV}) as F_0/V_0 [9]. However, controversy exists about the linearity of FV-relationships obtained from multi-joint movements [8].

The value of a test is highly dependent on its reliability, especially when evaluating individual data from high-performing athletes [10]. However, although several studies have evaluated the within-session reliability of FV-variables [11–18], limited attention has been directed towards the between-session reliability of these FV-variables in athletes. Additionally, only encoders and the flight time calculation method have been used for measurements of between-session reliability of the FV-variables [12, 13, 19]. Hence, the reliability of other commonly used methods such as force plates and leg press devices is unknown [11–18]. Furthermore, different devices and methods (e.g., force plates, linear position transducers, pneumatic resistance apparatus and the flight time calculation method) are used to assess the lower limb FV-variables, but the agreement among these has received limited attention [17, 20–22].

Giroux et al. [20] previously investigated the reliability and agreement among three measurement methods (accelerometry, linear position transducer and flight time calculation method) during vertical jumps. However, they reported only average values of force, velocity and power for each jump, and not the extrapolated FV-parameters (F_0, V_0, P_{max} and S_{FV}) that are increasingly used for individual training prescriptions [3–5, 23]. García-Ramos et al. [22] investigated the agreement across methods for CMJ (force platform, linear position transducer and flight time calculation method), but not SJ. As the test-retest reliability of the different methods for assessing individual FV-profiles is of crucial importance, it is of great interest to investigate the mentioned shortcomings in the literature.

A novel aspect of FV-profiling during vertical jumping is the possibility of obtaining the extrapolated variable V_0 and the calculated $S_{FV,}$ as there are numerous methods for assessing maximal force and maximal power [24]. Interestingly, S_{FV} and V_0 have previously shown poorer reliability than F_0 and P_{max} in vertical jumping [11]. Cuk et al. [25] hypothesized that this lower reliability might be due to the distance of extrapolation, as all measurements are performed closer to F_0 compared to V_0, in addition to the small range in loads assessed during incremental loading protocols in vertical jumping. These speculations were partly confirmed by García-Ramos et al. [26], who reported that the load range used to acquire the FV-profile significantly affects the reliability of V_0. Assessing loads close to F_0 is limited by the technical demand of jumping with heavy loads, while attempts closer to V_0 are limited by the subject's own bodyweight during vertical jumping. However, the bodyweight issue is not present during the leg press exercise, making it possible to assess loads closer to both F_0 and V_0, potentially improving the reliability for the FV-variables. It is therefore of great interest to investigate the reliability of the extrapolated FV-variables from commonly used vertical jumping exercises as well as from the leg press exercise.

The aim of the present study was to examine the i) test-retest reliability and ii) agreement across methods for assessing individual FV-profiles of the lower limbs in well-trained athletes.

Methods

Experimental approach and design

The participants in the present study underwent physical testing four times. The first two testing timepoints were separated by ~1 week, before a training period of 2~6 months. The two last timepoints were also separated by ~1 week (Figs 1 and 2).

The data were collected from multiple regional Olympic training and testing centers. Because not all facilities had the same testing capacities, the sample size differed across the measurement methods. Therefore, the main analysis in this study was performed on the participants tested under all methods (reliability and agreement), with an additional aggregated analysis including all participants, with varying sample sizes across methods (only reliability analysis). For the main analysis, the test leaders were constant, and for the aggregated analysis the test leaders and equipment differed across centers but were kept constant for each participant (sample sizes for all tests are presented in the results section). Written informed consent was obtained from all participants prior to commencing their involvement in the study.

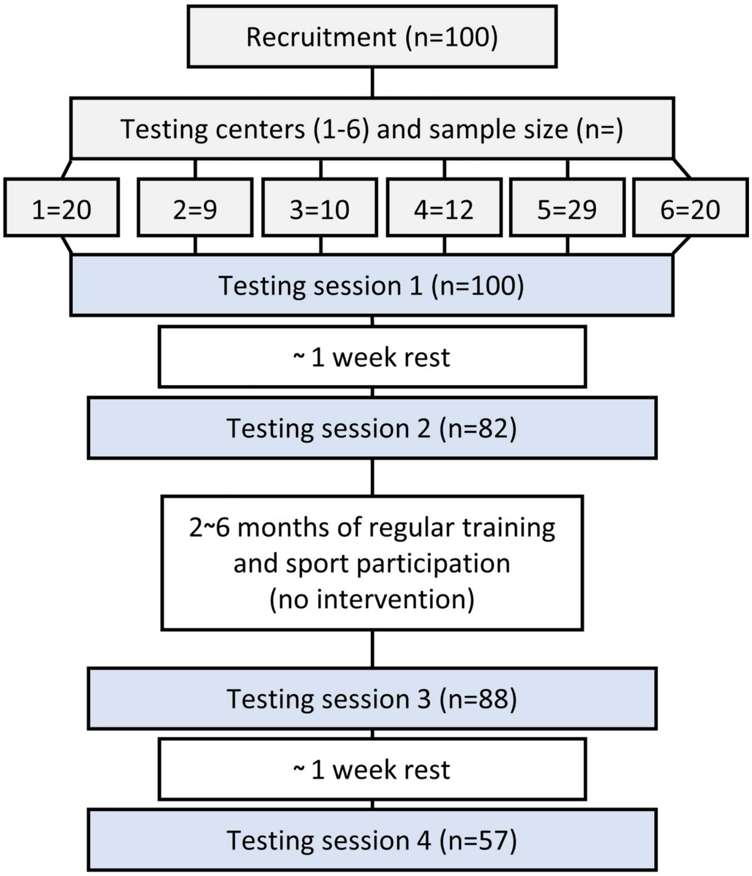

Fig 1. Flow chart representing study design.

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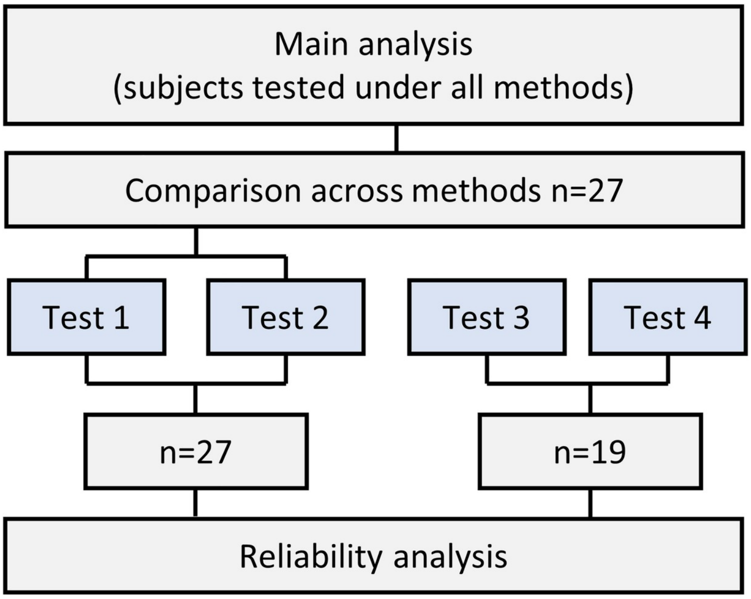

Fig 2. Flow chart representing study design and sample size for main analysis.

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The study was reviewed by the ethical committee of Inland Norway University of Applied Sciences, approved by the Norwegian Centre for Research Data and performed in agreement with the Declaration of Helsinki. The athletes in the main sample were familiar with the testing procedures, whereas the subjects in the mixed sample had various levels of experience prior to the study.

Participants. For the main analysis, a total of 27 well-trained male athletes from handball and ice hockey were included (age 21 ± 5 years; height 185 ± 8 cm; body mass 84 ± 13 kg; Table 1).

For the aggregated mixed sample, both male (approximately 80% of sample) and female athletes participated (age 21 ± 4 years; height 182 ± 9 cm; body mass 78 ± 12 kg; Table 2). Most of the participants were team sport players in handball, ice hockey, soccer, and volleyball, while the remaining participants competed in Nordic combined, ski jumping, weightlifting, athletics, badminton and speed skating. The competition level ranged from world class (Olympic medalist) to club level, with the majority competing at national and international level in their respective sports.

Testing procedures. All participants were instructed to prepare for the test days as they would for a regular competition in terms of nutrition, hydration, and sleep, and to refrain from strenuous exercise 48 hours prior to testing. All testing was performed indoors, and the participants were instructed to use identical footwear and clothing on each test day.

Bodyweight was measured wearing training clothes and shoes (as total bodyweight is used to calculate force in some of the methods). All participants performed a standardized ~10-min

Table 1. Performance characteristics of the athletes for main analysis.

	Mean ± SD	*Max*	*Min*
CMJ (cm)	38 ± 4	43	28
SJ (cm)	36 ± 4	43	28

Values from baseline measures, sample size = 27, SJ: Squat jump, CMJ: Countermovement jump, cm: Centimeters, s: seconds, SD: Standard deviation.

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Table 2. Performance characteristics of the athletes for aggregated analysis.

	n =	*Mean ± SD*	*Max*	*Min*
CMJ (cm)	*83*	38 ± 5	58	25
SJ (cm)	*72*	35 ± 6	51	22

Values from baseline measures, sample size in table. SJ: Squat jump, CMJ: Countermovement jump, Centimeters, s: seconds, SD: Standard deviation.

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warm-up procedure prior to testing, consisting of jogging, local muscle warm-up (hamstring and hip mobility–consisting of light dynamic stretches), running drills (e.g. high knees, skipping, butt-kicks, explosive lunges) and bodyweight jumps.

The different tests were separated by 5–10 min to ensure proper recovery, and light snacks and drinks were offered to the participants during the testing sessions. The testing protocol consisted of a series of squat jumps (SJ), countermovement jumps (CMJ) and a leg press test with incremental loads.

SJ and CMJ were initially performed with bodyweight, accompanied by an incremental loading protocol consisting of 0.1 (broomstick), 20, 40, 60 and 80 kg. In the aggregated sample, for some weaker participants (i.e., those unable to jump with 80 kg), a protocol of approximately 5 loads up to 80% of bodyweight was used. The increase in loads was then individually determined. In both the SJ and CMJ, the FV-relationship was derived from a force plate (For main analysis: Musclelab; Ergotest AS, Porsgrunn, Norway and for aggregated analysis some tested at: AMTI; Advanced Mechanical Technology, Inc Waltham Street, Watertown, USA) and a linear position transducer encoder (Ergotest AS, Porsgrunn, Norway). The encoder was placed on the ground and connected to the barbell. Participants were instructed to keep their hands on their hips for the bodyweight trials, and a broomstick was used as the 0.1 kg load. Two valid trials were registered for each load. The recovery after each attempt was 2–3 min.

For the SJ, participants were asked to maintain their individual starting position (∼90˚ knee angle) for about 2 s and then apply force as fast as possible and jump to the maximum possible height before landing with their ankles in an extended position. Countermovement was not allowed for the SJ and was checked visually with the direct force output from the force plate. The starting position for both SJ and CMJ was standardized to the athlete's self-selected starting position and kept constant for all jumps and testing sessions. The starting position for the SJ and the depth of the CMJ was controlled using a rubber band beneath the thighs of the athletes. If these requirements were not met, the trial was repeated. The CMJ test procedure was similar to that for SJ, except for the pause in the bottom position.

For the leg press, Keiser Air300 horizontal pneumatic leg press equipment with an A420 force and velocity measuring device (Keiser Sport, Fresno, CA) was used. The FV-variables were derived from a 10-repetition FV-test pre-programmed in the Keiser A420 software. To determine the loading range, each participant's 1RM was obtained at the familiarisation session for the main analysis, whereas the 1RM was individually estimated for the participants in the aggregated analysis. The test started with two practice attempts at the lightest load, corresponding to ∼15% of 1RM. Thereafter, the load was gradually increased with fixed steps (∼20–30 kgf) for each attempt until reaching the ∼1RM load and a total of 10 attempts across the FV-curve (15–100% of 1RM). The rest period between attempts got longer as the load increased. The rest period between attempts was ∼10–20 seconds for the initial five loads, and 20–40 seconds for the last four loads. The seating position was adjusted for each participant, aiming at a vertical femur, equivalent to an 80-90˚ knee angle, and the feet were placed with the heels at the lower end of the foot pedal. Participants were asked to extend both legs using maximum effort during the entire 10-repetition FV-test. Due to the pneumatic semi-isotonic resistance, maximal effort does not cause ballistic action, and the entire push-off was performed with maximal intentional velocity. The leg press was performed as a concentric-only action without countermovement, as the pedals were resting in their predetermined position prior to each repetition. The eccentric phase was submaximal and not registered.

Data analysis

All FV-variables were obtained from the average force and velocity during the concentric phase of the movement. For each incremental loading test, a linear regression was fitted to the average force and velocity measurements to calculate the individual FV-variables. F_0 and V_0 were defined as the intercepts of the linear regression for the corresponding force and velocity axis, while S_{FV} refers to the slope of the linear regression. P_{max} was then calculated as $F_0 \cdot V_0/4$. All FV-variables were obtained from FV-profiles with a coefficient of determination greater than 0.95 [9].

Force plate: FV-variables derived from the force plate were analysed using a customized Microsoft Excel spreadsheet (Microsoft Office Professional Plus 2018, version 16.23). Velocity was calculated by integrating the acceleration obtained from the ground reaction forces. The centre of mass position was the integral of velocity, while power was the product of force and velocity [27]. The start of the concentric phase for the SJ was defined as the point at which force exceeded 5 SD of the steady-stance weight prior to the jump [27–29]. For the CMJ, the integration of velocity started when the force fell below 5 SD of the steady-stance weight. The concentric phase was defined as the point at which velocity was greater than 0 m/s. The end of the concentric phase for both SJ and CMJ was defined as the instant when the participant left the force plate (i.e., take-off: when forces fell below 10N).

Encoder: By measuring the position of the cable (connected to the bar) as a function of time, the software calculates force and velocity (MuscleLab, version 10.5.69.4815). Average force was calculated as the product of mass and acceleration. Acceleration was calculated as the average velocity divided by the duration of the positive displacement, with the addition of the gravitation constant, while mass was calculated as bodyweight plus external load. In agreement with the manufacturer´s recommendation and previous studies [30], 90% of body mass and 100% of external load were used to calculate force during SJ and CMJ. *Flight time method*: Average force ($\bar{F}$) and average velocity ($\bar{v}$) were calculated using two equations, considering only simple input variables: body mass, jump height and push-off distance [15, 31]. The vertical push-off distance was determined as previously proposed [9], corresponding to the difference between the extended lower limb length with maximal foot plantar flexion and the crouch starting position of the jump.

Keiser leg press: The Keiser Air300 horizontal leg press dynamometer uses pneumatic resistance and measures compression forces at the cylinder, while velocity is measured with a position transducer. The values at the cylinder are then calculated to match the range of motion and velocity at the apparatus pedals [1]. Average force and velocity were calculated as a function of time, where the software excludes 5% of the range of motion from the start and end of the movement.

The measurement sample rate for the MuscleLab force plate and encoder was 200 Hz and for the leg press apparatus was 400 Hz. The force signal from the Musclelab force plate data was upsampled to 1000 Hz by spline integration using the integrated software. The AMTI force plate sampled at 2000 Hz.

Statistical analysis

The coefficient of variation (CV%), interclass correlation coefficient (ICC 3,1) and mean percent change (%Δ) were used to assess reliability across the testing sessions. CV% and %Δ were calculated from the log-transformed data. The Pearson product-moment correlation coefficient (Pearson r) was used to determine the association across methods. For comparison across methods, the mean difference (systematic bias) was calculated and presented in absolute and in relative terms (% from log transformed data) with percent and standardized difference (mean difference divided by the standard deviation of the criterion measure).

The standardized difference was qualitatively interpreted using the scale (<0.2 Trivial; 0.2–0.6 Small; 0.6–1.2 Moderate; 1.2–2.0 Large; 2.0–4.0 Very large; >4.0 Extremely large) [32]. A paired sample t-test was used to test the significance level of the differences in means. Additionally, a linear regression analysis with corresponding slope and Y-intercept of the regression line was used for comparison across methods. The standard error of the estimate (SEE) was calculated from the linear regression and presented in absolute and relative terms. For comparison across methods, the averages of the two first testing timepoints were included.

The smallest worthwhile change (SWC%) was calculated as 0.2 of the between-athlete SD, presented as a percentage of the mean. Confidence limits (CL) for all analyses were set at 95%. The Pearson's r coefficients were interpreted categorically (<0.09 trivial; 0.10–0.29 small; 0.30–0.49 moderate; 0.50–0.69 large; 0.70–0.89 very large; 0.90–0.99 nearly perfect; 1.00 perfect) as defined by Hopkins and Marshall [33].

Acceptable reliability was considered as ICC $\geq$ 0.80 and CV $\leq$ 10%, while good reliability was considered as ICC $\geq$ 0.90 and CV $\leq$ 5% [34–41]. Descriptive data are reported as mean ± SD. All statistical analyses were performed using a customized Microsoft Excel spreadsheet [32].

Results

Test-retest reliability of the FV-variables

All FV-profiles displayed linearity, with individual R^2 values ranging from 0.95 to 1.00. All the following results presented in the text correspond to results from the main analysis, whereas results from the aggregated analysis are only presented in tables. Fig 3 and Table 3 show the reliability measures of the FV-variables for the main analysis. Table 4 shows the reliability measures of the FV variables for the aggregated analysis.

Of all the investigated measurement methods, only the leg press showed acceptable reliability for the four FV-variables (CV: 3.7–8.3%, ICC: 0.82–0.98). Several of the measures for P_{max} and F_0 obtained from the vertical jumps showed acceptable reliability (CV: 3.9–12.1%, ICC: 0.61–0.97) (Table 3). However, V_0 and S_{FV} showed unacceptable reliability for all the investigated SJ and CMJ measurement methods (CV: 8.4–30.1%, ICC: 0.16–0.79). The typical error for both SJ and CMJ jump height was 1.2 cm, corresponding to a coefficient of variation of 6.8%. For each loading condition (0, 20, 40, 60 and 80 kg) the typical error was: 1.7, 1.2, 0.9, 1.0 and 1.0 cm corresponding to a CV of 5.1, 4.6, 5.5, 7.6 and 10.2% respectively.

Agreement across methods

The agreement and comparisons for the different measurement methods are shown in Table 5. Mean±SD values for all the FV-methods are shown in Table 6 and illustrated in Fig 4. The agreement across methods for F_0 and P_{max} ranged from (Pearson r): 0.56–0.95, SEE%: 5.8–18.8, and for V_0 and S_{FV} r: -0.39–0.78, SEE%: 12.2–37.2. The mean bias for F_0 ranged from trivial to moderate (-6-14%, ES: -0.4–0.9); small to large for P_{max} (-30-55%, ES: -1.8–1.7); trivial to very large for V_0 (-35-70%, ES: -2.8–2.2); and small to very large for S_{FV} (-32-165%, ES: -1.2–3.8) (Tables 5 and 6 and Fig 4).

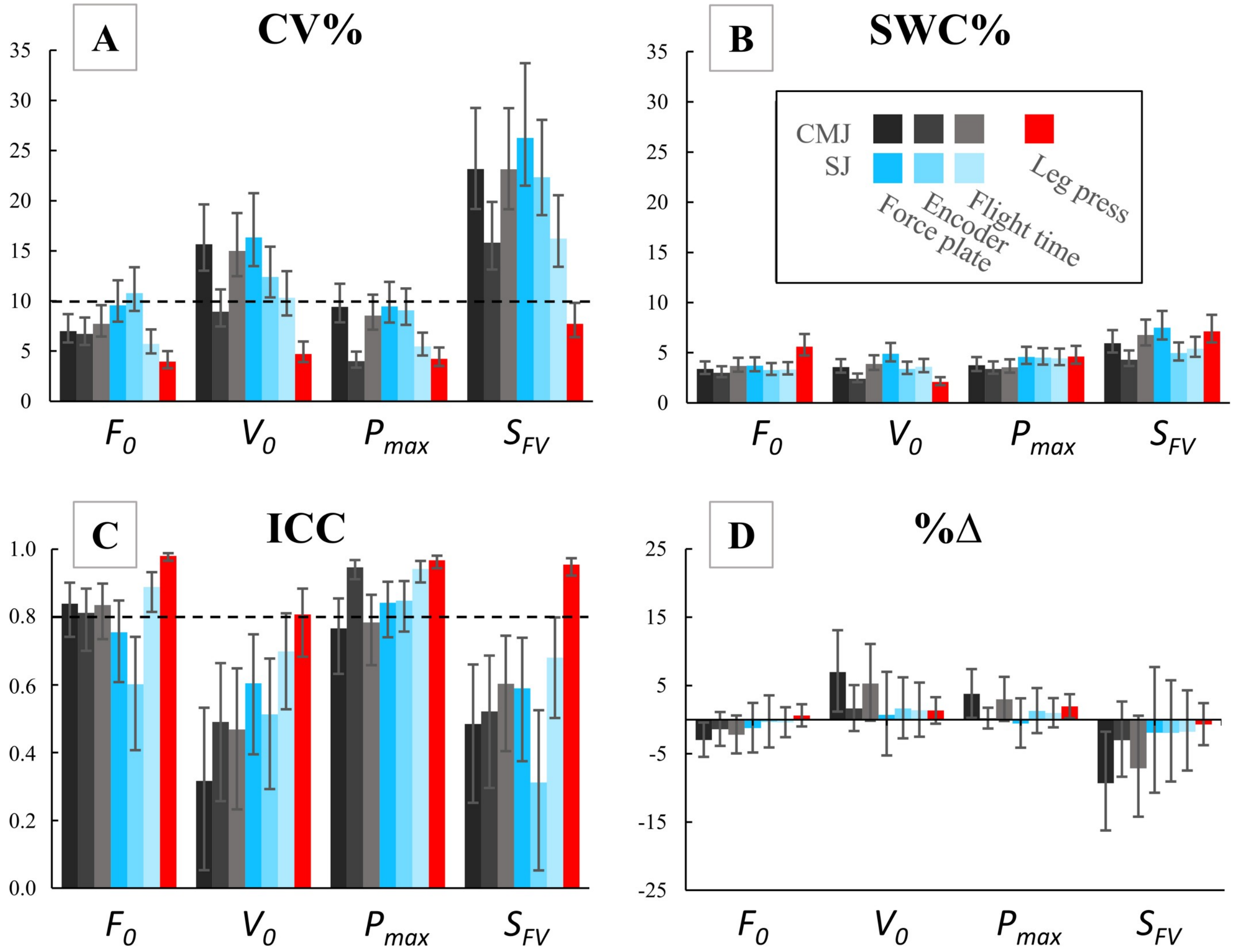

Fig 3. Measures of reliability for the FV variables obtained from main analysis. Panel A- Coefficient of variation (CV%), panel B- Smallest worthwhile change (SWC%), panel C- Interclass correlation coefficient (ICC), panel D- Mean % change (%Δ). All values were obtained by combining test 1–2 (n = 27) and 3–4 (n = 19). Error bars represent 95% confidence intervals. Dotted line represents line of acceptable reliability.

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Discussion

This is the first study to investigate the between-session reliability of FV-profiles measured in SJ and CMJ with a force plate, linear encoder, and a flight time calculation method, in addition to a leg press task. The main finding of the present study was that regardless of strong linearity for individual FV-profiles, S_{FV} and V_0 were unreliable for all measurement methods assessed from vertical jumping using loads ranging from bodyweight to 80 kg (relative position on the FV-curve, force values 40–70% of F_0). Only the leg press exercise showed acceptable reliability for the four FV-variables (relative position on the FV-curve, force values 20–80% of F_0). There was a large to nearly perfect association across measurement methods for F_0 and P_{max}, while the association for V_0 and S_{FV} ranged from trivial to large.

Test-retest reliability of the FV-variables

To the authors' knowledge, this is the first study to assess the test-retest reliability of the FV-variables in well trained and elite athletes. The present results are in accordance with previous

Table 3. Measures of reliability for the FV variables obtained from the main analysis with corresponding 95% confidence intervals.

		Coefficient of variation (CV%)				*Interclass correlation (ICC)*				*Percent change (%Δ)*			
	Test	F_0	V_0	P_{max}	S_{FV}	F_0	V_0	P_{max}	S_{FV}	F_0	V_0	P_{max}	S_{FV}
CMJ Force plate	*1–2*	**8.6 ± 2.6**	19.2 ± 6.2	10.8 ± 3.4	29.0 ± 9.8	**0.81 ± 0.14**	0.20 ± 0.37	0.74 ± 0.18	0.40 ± 0.32	-2.3 ± 4.5	6.5 ± 10.5	4.0 ± 6	-8.3 ± 13.1
	3–4	**5.1 ± 1.8**	12.6 ± 4.6	8.8 ± 3.1	17.5 ± 6.5	**0.89 ± 0.10**	0.16 ± 0.43	0.77 ± 0.19	0.47 ± 0.34	-2.6 ± 3.1	7.1 ± 8.2	4.3 ± 5.7	-9.1 ± 9.5
CMJ Encoder	*1–2*	**6.8 ± 2**	9.8 ± 2.9	**4.4 ± 1.3**	16.9 ± 5.2	**0.82 ± 0.13**	0.43 ± 0.30	**0.95 ± 0.04**	0.47 ± 0.29	-3.1 ± 3.4	3.9 ± 5.2	0.6 ± 2.3	-6.7 ± 7.8
	3–4	7.0 ± 2.5	8.4 ± 3.1	**3.9 ± 1.4**	15.5 ± 5.9	0.78 ± 0.19	0.44 ± 0.37	**0.95 ± 0.04**	0.38 ± 0.39	1.4 ± 4.5	-1.8 ± 5.3	-0.4 ± 2.5	3.2 ± 9.9
CMJ Flight time	*1–2*	10.1 ± 3.1	18.7 ± 6	9.6 ± 2.9	30.1 ± 10.2	0.79 ± 0.15	0.29 ± 0.35	0.74 ± 0.18	0.50 ± 0.29	-3.0 ± 5.2	4.4 ± 10	1.2 ± 5.2	-7.1 ± 13.7
	3–4	**5.2 ± 1.8**	11.8 ± 4.3	**7.8 ± 2.8**	16.9 ± 6.3	**0.92 ± 0.08**	0.70 ± 0.23	**0.82 ± 0.15**	0.79 ± 0.18	-1.7 ± 3.2	7.7 ± 7.8	5.9 ± 5.1	-8.8 ± 9.2
SJ Force plate	1–2	11.2 ± 3.5	17.4 ± 5.6	**9.4 ± 2.9**	29.3 ± 9.9	0.69 ± 0.21	0.60 ± 0.25	**0.87 ± 0.10**	0.51 ± 0.29	0.5 ± 6.0	-2.7 ± 8.8	-2.2 ± 4.9	3.2 ± 14.9
	3–4	**6.7 ± 2.4**	15.4 ± 5.7	**10 ± 3.6**	22.3 ± 8.5	**0.84 ± 0.13**	0.54 ± 0.32	**0.81 ± 0.16**	0.57 ± 0.30	-2.2 ± 4.1	4.1 ± 9.6	1.8 ± 6.2	-6.0 ± 12.2
SJ Encoder	*1–2*	12.1 ± 3.5	11.1 ± 3.2	11.5 ± 3.4	21.0 ± 6.4	0.61 ± 0.24	0.59 ± 0.24	0.81 ± 0.13	0.36 ± 0.32	2.0 ± 6.1	-1.4 ± 5.5	0.6 ± 5.8	3.4 ± 10.4
	3–4	6.5 ± 2.2	10.2 ± 3.6	**5.2 ± 1.8**	16.9 ± 6.1	0.77 ± 0.18	0.62 ± 0.27	**0.94 ± 0.05**	0.42 ± 0.36	-3.0 ± 3.8	6.0 ± 6.5	2.9 ± 3.3	-8.5 ± 9.0
SJ Flight time	*1–2*	**5.2 ± 1.6**	8.6 ± 2.6	**4.4 ± 1.3**	13.9 ± 4.4	**0.92 ± 0.06**	0.79 ± 0.16	**0.97 ± 0.03**	0.76 ± 0.17	0.8 ± 2.9	-2.7 ± 4.5	-1.9 ± 2.4	3.7 ± 7.5
	3–4	**6.4 ± 2.3**	11.6 ± 4.2	**5.8 ± 2**	18.5 ± 7.0	**0.86 ± 0.13**	0.63 ± 0.27	**0.93 ± 0.07**	0.62 ± 0.28	-1.7 ± 3.9	6.7 ± 7.6	4.9 ± 3.8	-7.9 ± 10.1
Keiser leg press	*1–2*	**4.2 ± 1.3**	**5.0 ± 1.5**	**4.2 ± 1.3**	**8.3 ± 2.5**	**0.98 ± 0.02**	**0.82 ± 0.14**	**0.97 ± 0.02**	**0.95 ± 0.04**	0.2 ± 2.3	2.2 ± 2.8	2.4 ± 2.4	-2.0 ± 4.4
	3–4	**3.7 ± 1.4**	**4.3 ± 1.6**	**4.2 ± 1.6**	**7.0 ± 2.6**	**0.98 ± 0.02**	**0.82 ± 0.16**	**0.97 ± 0.03**	**0.96 ± 0.04**	1.3 ± 2.5	0.4 ± 2.9	1.7 ± 2.9	0.9 ± 4.6

Bold text denotes CV<10% and ICC>0.80. Sample size for test 1–2 = 27, and test 3–4 = 19. SJ: Squat jump, CMJ: Countermovement jump, F_0:Theoretical maximal force, V_0: Theoretical maximal velocity, P_{max}: Theoretical maximal power, S_{FV}: slope of the force-velocity profile.

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research in other populations showing mostly acceptable reliability for F_0 and P_{max} (CV<10%) and poor reliability for V_0 and S_{FV} (CV >10%) during vertical jumping [12, 19, 25, 42, 43]. In contrast, FV-profiles derived from the leg press exercise displayed acceptable reliability for all variables in the present study (CV<10%, ICC>0.8). Feeney et al. [11] proposed that the low reliability

Table 4. Measures of reliability for the FV variables obtained from aggregated analysis with corresponding 95% confidence intervals.

			Coefficient of variation (CV%)				*Interclass correlation (ICC)*				*Percent change (%Δ)*			
	Test	*n =*	F_0	V_0	P_{max}	S_{FV}	F_0	V_0	P_{max}	S_{FV}	F_0	V_0	P_{max}	S_{FV}
CMJ Force plate	*1–2*	*34*	**8.0 ± 2.1**	17.5 ± 4.9	9.9 ± 2.7	26.5 ± 7.7	**0.81 ± 0.12**	0.22 ± 0.32	0.76 ± 0.15	0.40 ± 0.29	-3.2 ± 3.7	6.9 ± 8.5	3.4 ± 4.8	-9.4 ± 10.5
	3–4	*21*	**5.1 ± 1.8**	12.6 ± 4.6	8.8 ± 3.1	17.5 ± 6.5	**0.89 ± 0.10**	0.19 ± 0.43	0.78 ± 0.18	0.45 ± 0.35	-2.6 ± 3.1	7.1 ± 8.2	4.3 ± 5.7	-9.1 ± 9.5
CMJ Encoder	*1–2*	*82*	**6.8 ± 1.1**	8.6 ± 1.4	**4.0 ± 0.6**	15.5 ± 2.6	**0.89 ± 0.05**	0.74 ± 0.10	**0.96 ± 0.02**	0.78 ± 0.09	-2.4 ± 2.0	2.2 ± 2.6	-0.3 ± 1.2	-4.5 ± 4.3
	3–4	*56*	**7.3 ± 1.5**	9.4 ± 1.9	**3.7 ± 0.7**	17.0 ± 3.6	**0.81 ± 0.09**	0.51 ± 0.19	**0.96 ± 0.02**	0.48 ± 0.20	-0.7 ± 2.6	0.5 ± 3.4	-0.2 ± 1.4	-1.1 ± 5.9
CMJ Flight time	*1–2*	*34*	**9.0 ± 2.4**	16.8 ± 4.7	8.8 ± 2.4	26.7 ± 7.8	**0.80 ± 0.13**	0.31 ± 0.31	0.78 ± 0.14	0.51 ± 0.26	-2.5 ± 4.2	3.8 ± 8.0	1.2 ± 4.2	-6.1 ± 11
	3–4	*21*	**5.2 ± 1.8**	11.8 ± 4.3	**7.8 ± 2.8**	16.9 ± 6.3	**0.92 ± 0.08**	0.69 ± 0.24	**0.81 ± 0.16**	0.78 ± 0.18	-1.7 ± 3.2	7.7 ± 7.8	5.9 ± 5.1	-8.8 ± 9.2
SJ Force plate	1–2	45	10.8 ± 2.5	15.3 ± 3.6	**8 ± 1.8**	26.6 ± 6.6	0.71 ± 0.15	0.64 ± 0.18	**0.87 ± 0.07**	0.59 ± 0.20	-1 ± 4.3	-1.6 ± 6	-2.7 ± 3.2	0.6 ± 10.1
	3–4	40	11.6 ± 2.9	19.6 ± 5	11.5 ± 2.8	31.8 ± 8.6	0.61 ± 0.20	0.43 ± 0.26	0.73 ± 0.15	0.42 ± 0.26	-7.1 ± 4.6	8.4 ± 8.8	0.7 ± 4.9	-14.3 ± 10.7
SJ Encoder	*1–2*	*34*	12.1 ± 3.3	11.6 ± 3.2	10.9 ± 2.9	22.0 ± 6.3	0.58 ± 0.23	0.54 ± 0.25	0.82 ± 0.12	0.28 ± 0.31	0.3 ± 5.6	0.4 ± 5.5	0.8 ± 5.1	-0.1 ± 9.8
	3–4	*23*	8.7 ± 3.0	13.6 ± 4.7	**5.9 ± 1.9**	23.2 ± 8.4	0.63 ± 0.26	0.39 ± 0.36	**0.92 ± 0.07**	0.14 ± 0.42	-1.3 ± 5.1	3.4 ± 8.1	2.0 ± 3.5	-4.6 ± 12.2
SJ Flight time	*1–2*	*47*	**5.6 ± 1.2**	8.9 ± 2.0	**4.8 ± 1.0**	14.5 ± 3.3	**0.89 ± 0.06**	0.77 ± 0.13	**0.96 ± 0.02**	0.70 ± 0.15	-0.8 ± 2.2	-0.8 ± 3.5	-1.6 ± 1.9	-0.1 ± 5.6
	3–4	*33*	**6.7 ± 1.8**	11.5 ± 3.2	**5.6 ± 1.5**	18.6 ± 5.3	**0.81 ± 0.12**	0.68 ± 0.19	**0.94 ± 0.04**	0.58 ± 0.23	-1.2 ± 3.2	3.7 ± 5.6	2.4 ± 2.8	-4.7 ± 8.2
Keiser leg press	*1–2*	*66*	**4.7 ± 0.9**	**5.1 ± 0.9**	**4.2 ± 0.8**	**9.0 ± 1.7**	**0.96 ± 0.02**	**0.83 ± 0.08**	**0.98 ± 0.01**	**0.91 ± 0.04**	1.8 ± 1.6	-0.4 ± 1.7	1.2 ± 1.5	2.2 ± 3.0
	3–4	*45*	**4.1 ± 0.9**	**4.5 ± 1.0**	**4.0 ± 0.9**	**7.6 ± 1.7**	**0.97 ± 0.02**	**0.86 ± 0.08**	**0.98 ± 0.01**	**0.94 ± 0.04**	0.3 ± 1.7	0.0 ± 1.9	-0.2 ± 1.7	0.2 ± 3.1

Bold text denotes CV<10% and ICC>0.80. sample size in table. SJ: Squat jump, CMJ: Countermovement jump, F_0:Theoretical maximal force, V_0: Theoretical maximal velocity, P_{max}: Theoretical maximal power, S_{FV}: slope of the force-velocity profile.

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Table 5. Agreement and comparison for CMJ Force plate and SJ Force plate vs encoder, flight time and leg press measurements.

			Mean bias (±SD)	Mean bias % (±SD)	Standardized difference (±CL)	SEE (±CL)	SEE % (±CL)	Pearson r (±CL)	Slope of regression line	Y-intercept of regression line
CMJ Force plate VS	CMJ Encoder	F_0 (N)	19 ± 233	1.2 ± 8.9	0.0 ± 0.2	238 ± 71	8.6 ± 2.7	0.865 ± 0.108*	1.03	-88
		V_0 (m/s)	-1.0 ± 0.5**	-22.8 ± 15.6	-1.7 ± 0.3	0.5 ± 0.2	14.4 ± 4.6	0.508 ± 0.293*	0.89	1.3
		P_{max} (W)	-643 ± 248**	-22.2 ± 9.9	-1.3 ± 0.2	243 ± 72	9.5 ± 3.0	0.878 ± 0.098*	1.19	275
		S_{FV} (N/m/s)	256 ± 174**	44.1 ± 25.5	1.3 ± 0.3	163 ± 49	23.2 ± 7.8	0.597 ± 0.258*	0.64	110
	CMJ Flight Time	F_0 (N)	11 ± 180	0.0 ± 6.9	0.0 ± 0.2	152 ± 45	5.8 ± 1.8	0.947 ± 0.045*	0.81	507
		V_0 (m/s)	-0.8 ± 0.5**	-19.3 ± 17.2	-1.4 ± 0.3	0.5 ± 0.1	13.9 ± 4.5	0.562 ± 0.272*	0.71	1.6
		P_{max} (W)	218 ± 199**	31.4 ± 24	1.1 ± 0.4	126 ± 38	18.8 ± 6.2	0.783 ± 0.161*	0.50	267
		S_{FV} (N/m/s)	-550 ± 296**	-19.4 ± 13.3	-1.1 ± 0.2	302 ± 90	12.2 ± 3.9	0.802 ± 0.149*	1.00	545
	Leg press	F_0 (N)	415 ± 500**	13.6 ± 17.8	0.9 ± 0.4	246 ± 73	9.5 ± 3.0	0.855 ± 0.115*	0.48	1243
		V_0 (m/s)	-1.6 ± 0.6**	-34.8 ± 21.3	-2.8 ± 0.4	0.6 ± 0.2	16.8 ± 5.5	0.106 ± 0.376	0.27	3.2
		P_{max} (W)	-895 ± 253**	-30 ± 14.2	-1.8 ± 0.2	255 ± 76	10.7 ± 3.4	0.865 ± 0.108*	1.10	723
		S_{FV} (N/m/s)	764 ± 444**	164.6 ± 42.7	3.8 ± 0.9	177 ± 53	26.4 ± 9.0	0.490 ± 0.299*	0.19	460
SJ Force plate VS	SJ Encoder	F_0 (N)	-194 ± 294**	-6.3 ± 10.9	-0.4 ± 0.2	300 ± 89	10.3 ± 3.2	0.817 ± 0.140*	0.96	310
		V_0 (m/s)	0.0 ± 0.5	2.6 ± 21.7	0.1 ± 0.3	0.5 ± 0.1	19.9 ± 6.6	0.548 ± 0.278*	0.93	0.2
		P_{max} (W)	215 ± 251**	12.1 ± 12.4	0.5 ± 0.2	203 ± 60	11.1 ± 3.5	0.892 ± 0.088*	0.72	350
		S_{FV} (N/m/s)	-278 ± 327**	-19.4 ± 36.3	-0.7 ± 0.3	331 ± 99	29.4 ± 10.2	0.569 ± 0.27*	0.85	421
	SJ Flight Time	F_0 (N)	-134 ± 400**	-4.4 ± 15.2	-0.3 ± 0.3	389 ± 116	13.5 ± 4.3	0.662 ± 0.228*	0.74	872
		V_0 (m/s)	0.2 ± 0.6**	11.4 ± 28	0.4 ± 0.4	0.5 ± 0.2	22.8 ± 7.7	0.405 ± 0.325*	0.47	1.2
		P_{max} (W)	99 ± 236**	5.8 ± 13.2	0.2 ± 0.2	224 ± 67	12.4 ± 4.0	0.866 ± 0.106*	0.82	244
		S_{FV} (N/m/s)	-186 ± 422**	-12.5 ± 51.2	-0.5 ± 0.4	394 ± 117	36.1 ± 12.9	0.207 ± 0.366	0.32	899
	Leg press	F_0 (N)	238 ± 704	6.0 ± 28.9	0.5 ± 0.5	437 ± 130	15.4 ± 5.0	0.541 ± 0.281*	0.33	1877
		V_0 (m/s)	-0.3 ± 0.7**	-11.7 ± 34.7	-0.6 ± 0.4	0.6 ± 0.2	24.0 ± 8.1	-0.177 ± 0.370	-0.45	3.5
		P_{max} (W)	-136 ± 187**	-7.2 ± 10.6	-0.3 ± 0.2	191 ± 57	10.1 ± 3.2	0.905 ± 0.078*	1.03	95
		S_{FV} (N/m/s)	276 ± 665**	23.5 ± 84.5	0.7 ± 0.7	401 ± 120	37.2 ± 13.3	-0.074 ± 0.378	-0.06	1327
	CMJ Force plate	F_0 (N)	-177 ± 424**	-5.9 ± 16.5	-0.3 ± 0.3	406 ± 121	14.0 ± 4.5	0.623 ± 0.246*	0.68	1042
		V_0 (m/s)	1.3 ± 0.8**	70.0 ± 34.7	2.2 ± 0.6	0.6 ± 0.2	24.6 ± 8.3	-0.015 ± 0.380	-0.02	2.5
		P_{max} (W)	759 ± 306**	54.8 ± 15.7	1.7 ± 0.3	274 ± 82	14.9 ± 4.8	0.793 ± 0.155*	0.70	1.0
		S_{FV} (N/m/s)	-488 ± 423**	-32 ± 62.9	-1.2 ± 0.4	400 ± 119	37.1 ± 13.3	0.105 ± 0.376	0.21	1083

Sample size = 27

*Significant correlations $p<0.05$

**Significantly different from comparison measure (SJ/CMJ force plate) $p<0.05$. SJ: Squat jump, CMJ: Countermovement jump, SEE: Standard error of estimate. SD: Standard deviation, CL: 95% Confidence limit.

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for V_0 (and thereby S_{FV}) during vertical jumping could be a consequence of calculating velocity from a force signal (force plate). However, our data show low reliability for V_0 from CMJ and SJ regardless of the velocity calculation method. The velocity from the leg press exercise is calculated as the derivation of position over time, identical to the encoder during SJ and CMJ, making it less likely that the variation in V_0 is caused by calculation error. Further, Meylan et al. [12] speculated that the low V_0 reliability is caused by greater biological variation closer to V_0. However, our data show similar typical errors across loads and similar typical errors for F_0 and V_0 from the leg press (using loads with similar distance to both intercepts), making this questionable.

Furthermore, García-Ramos et al. [26] showed that the low V_0 reliability during vertical jumping was most likely due to the distance of the extrapolation to the V_0 intercept [26], as the lightest load possible to assess is the subject's own bodyweight. The influence of the

Table 6. FV-variables for all methods.

	F_0 (N)	V_0 (m/s)	P_{max} (W)	S_{FV} (N/m/s)
CMJ Force plate	2741 ± 491	3.8 ± 0.7	2537 ± 527	771 ± 260
CMJ Encoder	2760 ± 415	2.8 ± 0.4	1906 ± 360	1016 ± 225
CMJ Flight time	2759 ± 549	3.1 ± 0.6	2090 ± 380	948 ± 346
SJ Force plate	2915 ± 561	2.5 ± 0.7	1806 ± 464	1249 ± 483
SJ Encoder	2621 ± 404	2.5 ± 0.4	1652 ± 361	1065 ± 244
SJ Flight time	2794 ± 476	2.7 ± 0.5	1925 ± 498	1059 ± 270
Keiser leg press	3156 ± 831	2.1 ± 0.2	1660 ± 389	1519 ± 510

Sample size = 27. SJ: Squat jump, CMJ: Countermovement jump, F_0:Theoretical maximal force in newtons, V_0: Theoretical maximal velocity in meters per second, P_{max}: Theoretical maximal power in watts, S_{FV}: slope of the force-velocity profile. Values are presented as mean ± standard deviation.

https://doi.org/10.1371/journal.pone.0245791.t006

extrapolation distance has been discussed earlier [25], and the present results reinforce this assumption. F_0 and V_0 displayed similar reliability in the leg press exercise as the loads approached both ends of the FV-spectrum. The high reliability in the FV-variables obtained from the leg press can also partly be attributed to better standardisation in terms of fixed seat position, and thereby less technical variation in the exercise execution compared to the free weight conditions during CMJ and SJ [17, 18, 44, 45]. The influence of standardisation is also supported by the findings of Valenzuela et al. [19], which showed superior reliability of the FV variables obtained using a smith machine compared to free weights. It is therefore likely that the observed variations in the extrapolated variables V_0 and S_{FV} are caused by extrapolation error (i.e., small variations in the individual attempts are amplified because of the "extrapolation distance") and the combination of technical/instrumental and biological variations. Consequently, in addition to superior standardisation compared to the other tests, the larger load range in the leg press exercise reduces the need for extrapolation for both force and velocity, explaining the high reliability of all the FV variables (Table 7).

The FV variables showed some slight differences in reliability between the CMJ and SJ conditions (Table 3). These small differences can partly be explained by slope steepness differences between SJ and CMJ, as the extrapolation distance to each intercept varies between these conditions (Table 7 and Fig 4). Additionally, SJ is prone to integration errors when calculating velocity with the force plate method [29]. This is linked to the assumption of zero start velocity, which is technically more challenging during SJ compared to CMJ. This challenge is similar for the encoder method, as the average force and velocity are calculated at the instance of the encoder's registration of a positive displacement. These issues are reinforced by the fact that the flight time method showed the highest reliability for all FV-variables in SJ compared to the other methods (Table 3). Hence, the poor reliability of the SJ force plate and encoder method may be explained by calculation errors rather than physiological differences between the CMJ and SJ condition. Consequently, when calculating FV-profiles from encoders and force plates during SJ, careful attention should be given to the pause at the bottom (static position) of the squat to improve the detection of movement with this equipment (i.e., giving athletes extra practice attempts and/or familiarization).

Interestingly, the FV-variables measured with the encoder during CMJ exhibited the lowest CV% of all the CMJ measurement methods during the vertical jumps (Table 3). Notably, the encoder software uses the entire positive displacement curve, including the airtime. Additionally, average force is calculated as the product of mass and acceleration, where acceleration is the average velocity divided by the duration of the positive displacement. Especially in light loading conditions where the flight time is relatively long, changes and variability in force or

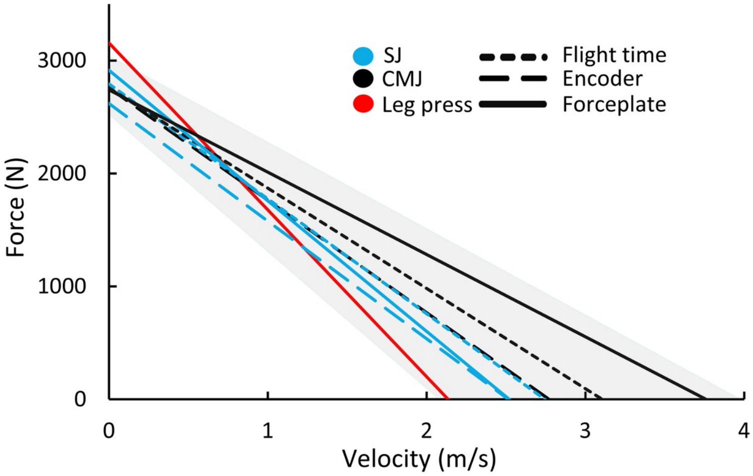

Fig 4. Shows averaged force-velocity profiles from all methods for the main analysis (n = 27). The shaded area represents the 95% confidence interval for the vertical jumps.

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velocity for the propulsive phase are inevitably harder to detect. Although the software manufacturer uses these calculations to improve reliability, the validity of the FV-profile will also be affected, considering the ability to detect changes. Additionally, changes in the estimated force in the light loading conditions are proportionally more affected by changes in bodyweight than changes in propulsive force (when the flight phase is greater than the push-off phase). With lower flight times, the encoder's measures will to a greater degree reflect changes in propulsive force. This is supported by the correlation of 0.86 for F_0 between the force plate method and the encoder. The greater reliability observed for the FV-variables assessed by the encoder may be misleading, as the usefulness of a test is determined not only by reliability and validity, but also by the ability to detect changes in performance [10].

The reliability results for the force plate method and flight time method were practically identical for all FV-variables during CMJ, but not SJ (Table 3). The differences between the force plate method and flight time method for SJ were probably due to the difficulty of detecting the zero starting velocity in the SJs for the force plate method, as discussed earlier [29]. This contention is supported by the fact that both methods (flight time and force plate method) showed similar reliability in the CMJ, as the zero starting velocity issue is not present in the CMJ. Furthermore, the slightly better reliability in SJ for the flight time method

Table 7. Loading ranges used to assess the force velocity profiles.

	Force in % of F_0		*Velocity in % of V_0*	
	Heaviest load	*Lightest load*	*Heaviest load*	*Lightest load*
CMJ Force plate	75 ± 6	56 ± 6	26 ± 6	46 ± 7
CMJ Encoder	63 ± 6	39 ± 6	37 ± 6	61 ± 6
CMJ Flight time	75 ± 7	56 ± 6	25 ± 7	46 ± 9
SJ Force plate	68 ± 10	50 ± 8	33 ± 9	56 ± 14
SJ Encoder	66 ± 7	37 ± 6	35 ± 7	63 ± 5
SJ Flight time	70 ± 10	52 ± 8	32 ± 9	58 ± 15
Keiser leg press	80 ± 9	18 ± 3	22 ± 8	84 ± 4

Sample size = 27. SJ: Squat jump, CMJ: Countermovement jump, F_0:Theoretical maximal force, V_0: Theoretical maximal velocity. Values are presented as mean ± standard deviation.

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compared to the CMJ condition was probably due to less variation in starting position, as this is easier to control with the pause at the bottom of the squat.

Conjointly, the reliability of F_0, V_0 and P_{max} was affected by the variation in the measurements–of each individual load–combined with the degree of extrapolation to the FV-intercepts. Hence, S_{FV} was inevitably affected by the variation in both F_0 and V_0. Researchers and coaches should be aware of these limitations when assessing individual FV-profiles. Indeed, the 5–10% CV in jump height observed in this study was not acceptable for accurately assessing the accompanying FV-variables V_0 and S_{FV}, regardless of measurement method, with a loading range of bodyweight to 80 kg (forces ranging from 40–70% of F_0). Typical error can only be decreased by reducing the variation in jumping performance or including loads closer to the F_0 and V_0 intercept. Additionally, the usefulness of a test is determined by the ability to detect changes in performance; more specifically, by comparing the typical error (CV%) with SWC [46]. Indeed, the FV-variables obtained from the leg press apparatus showed a superior signal-to-noise ratio compared to the other measurement methods in this study (Fig 3).

Agreement among methods

Calculating the velocity of the center of mass from ground reaction forces has previously shown comparable reliability, with only small measurement errors compared to the "gold standard" 3D motion capture systems [47, 48]. It can therefore be argued that the force-plate method is the most valid method for assessing FV-profile during vertical jumping compared to all other measurement methods used in this study.

Only a few studies have examined the relationships among varying FV-profile methods for the lower limbs. García-Ramos et al. [22] also observed strong correlations for F_0 and P_{max} and trivial correlations for V_0 and S_{FV} across methods (force plate, linear encoder and flight time methods). Similar to the present study, the poor agreement for V_0 and S_{FV} was explained by the large extrapolation error for V_0 [22].

Contrary to our findings, Jiménez-Reyes et al. [15] reported excellent agreement between the flight time and force plate method for the FV-variables (r: 0.98–0.99). This discrepancy from our findings can probably be attributed to several methodological differences. The flight time method calculates force and velocity based on jump height [15]. However, flight times are inevitably prone to small errors in technical execution [49], in addition to systematic errors compared to jump height obtained from force data [50, 51]. As Jiménez-Reyes et al. [15] point out, the FV-variables are associated with cumulative extrapolation errors, consecutively decreasing the validity of these variables. The small systematic and random differences in jump height between flight time and force data are even greater for the extrapolated FV-variables. Additionally, the assumption of constant acceleration during the push-off phase in the flight time method could also affect the agreement with the force plate method, as variations in average force and velocity during the push-off phase are not necessarily related to jump height variations [17, 18, 52, 53].

Furthermore, the flight time method assumes constant push-off distance across loads and trials [15, 31]. However, from the force plate data, we observed 5–10% (2–4 cm) variation in push-off distance across trials and loading conditions, even when controlling the depth as previously recommended [54]. This variation may be due to changes in jump mechanics across trials and loads [45], making it challenging to assume a constant push-off distance despite controlled knee angle. Jiménez-Reyes et al. [15] have previously reported a 0.4% variation (CV%) in push-off distance across trials for CMJ when using a smith machine. This apparatus probably reduces the variation in jump mechanics compared to the free weight jumps used in the present study. This implies that the poor agreement in our study can also be attributed to poor control of the center of mass for the subject, and not solely the flight time method.

Contrary to previous research showing an overestimation of V_0 measured with an encoder compared to a force plate (72.3%) [22, 47], we observed an underestimation for the CMJ condition (-23%) (Table 6). The overestimations of velocity during light loading conditions in previous investigations are explained by the attachment point at the bar, as the bar velocity is higher than the centre-of-mass velocity during jumping [22, 47]. However, because the velocity from the encoder used in this study is based on the entire positive displacement curve (including the airtime), the average velocity is lower. Combined with the extrapolation error, this partly explains the higher agreement between the force plate and encoder for F_0 and P_{max} compared with V_0 and S_{FV}. Practitioners and researchers should be aware of the limitations of using linear encoders for measuring FV-profiles, especially to obtain V_0 and S_{FV}.

Padulo et al. [21] observed an underestimation in V_0 (-46%) and overestimation in F_0 (21%) in the leg press compared to the squat exercise. The underestimation in V_0 can be attributed to biomechanical differences, as the squat movement involves a larger contribution from the hip joint, resulting in higher system velocity [21]. In addition, approximately 30% of the work during a vertical jump is contributed by the ankle joint [45]. This contribution is likely lower for the leg press due to the more plantarflexed orientation of the ankles in this apparatus. These biomechanical differences probably explain why the leg press has the largest bias of all the tested methods (Table 6). Another explanation is the pneumatic resistance in the present leg press apparatus, allowing higher average velocities for a given force due to the absence of inertia [55]. Additionally, the software excludes 5% of the range of motion from the start and end of the movement, inevitably affecting the average values in the lighter resistance conditions to a greater degree compared to the higher resistance conditions, resulting in higher V_0. These issues may explain the high V_0 in the leg press exercise and the low agreement in V_0 compared to the other measurement methods. Intriguingly, V_0 was negatively correlated with the three SJ measures and the leg press exercise (Fig 5). The extrapolated V_0 during the leg press exercise is highly influenced by the push-off distance [56], where it has been previously argued that comparisons across individuals should only be done when participants perform the vertical jumps with their usual or optimal push-off distance Samozino et al. [57]. The initial push-off distance during vertical jumping in this study was self-determined, while the push-off distance in the leg press was standardised, possibly explaining the poor correlation in V_0 between the leg press and the jump exercises. Furthermore, as shown by Bobbert [56], the linear shape of the FV-relationship during multi-joint movements is influenced by segmental dynamics, and this influence is magnified by increasing movement velocity [56]. Hence, segmental dynamics probably influence the agreement of V_0 to a greater degree than F_0 when comparing exercises with varying push-off distances and joint contributions [56]. Consequently, segmental dynamics partly explain the larger agreement for measures closer to F_0 and poorer agreement and correlations for V_0 across leg press and vertical jump tasks. As illustrated in Fig 4 and shown in Table 5, differences in V_0 are larger across methods and conditions compared to F_0.

Small but important differences across methods accumulate, with larger differences for V_0 and S_{FV} compared to F_0 and P_{max}. The agreement across methods is highly influenced by the combination of measurement errors, as well as the distance of extrapolation to the FV-intercepts. All FV-variables depend on the measurement condition, including equipment, exercise type, resistance modality and push-off distance.

Strengths and limitations

The present study included a large sample of male and female athletes with varying sport backgrounds, using a multicenter approach. This design allows for larger sample sizes and higher ecological validity as athletes are assessed by different test leaders and using different

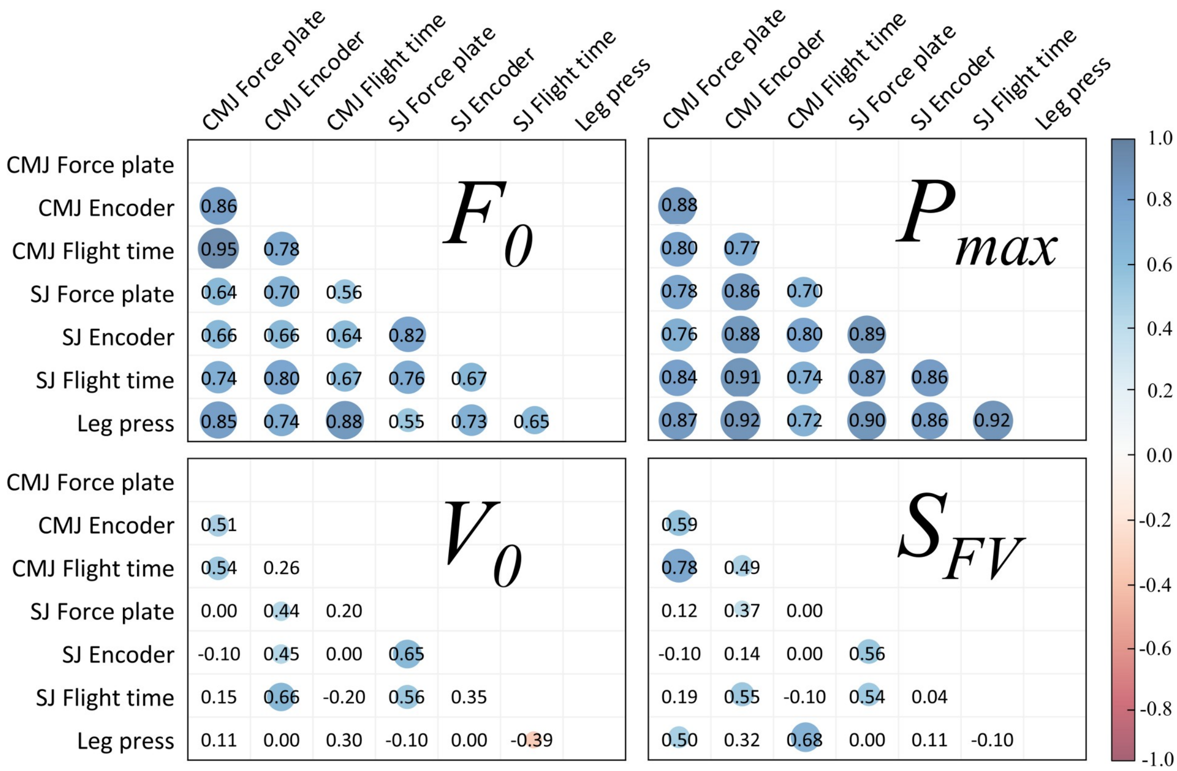

Fig 5. Correlation matrix showing Pearson r coefficients for the FV-profile variables (F_0, P_{max}, V_0, S_{FV}) for cross sectional data. Colored circles indicate $P<0.05$, where circle size and color represent corresponding r values (color legend is presented with the figure). SJ: Squat jump, CMJ: Countermovement jump, F_0: Theoretical maximal force, V_0: Theoretical maximal velocity, P_{max}: Theoretical maximal power, S_{FV}: slope of the force-velocity profile. Sample size for all correlations n = 27.

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equipment [58]. The conclusions from the study are based on the results from the main analysis and supported by the data from the larger aggregated analysis.

There are several methodological limitations that need to be considered for the findings from this study. The difference in number of loading conditions (i.e., 5 for vertical jumping and 10 for leg press) and relative position on the FV-curve inevitably affect the agreement measures due to differences in the accuracy of obtaining the extrapolated variables. Additionally, the difference in push-off distance from the leg press (standardized to vertical femur) and vertical jumping (standardized to self-selected depth) may influence the variation across these conditions. The leg press protocol included breaks of 10–20 sec for the light loads and 20–40 for the heavy loads, which may cause some fatigue between repetitions and influence the FV-relationship. For the force plate method, the 5 SD threshold for determining the start of the movement will influence the average values of force and velocity and thereby the FV-variables. Especially in the SJ, but also in the CMJ, this threshold is sensitive to small movements and is a source of error that is not controlled for. In the leg press software, the average values have a 5% cut-off from the range of movement, which can lead to i) taller athletes having a larger cut-off in terms of absolute values compared to shorter athletes, and ii) in the lighter loads where more range of motion is achieved, the cut-off in terms of absolute values will be larger for lighter loads compared to heavier loads. The results from the encoder used in the present study cannot be generalized to other linear encoder devices with different calculation methods for acceleration and force. The jumps in this study were performed with free weights, where it was difficult to accurately standardize the center of mass of the jumps using only thigh depth or knee angle as a reference. These variations in the center of mass are likely smaller using smith machines. These limitations inevitably affect both the test-retest reliability and the agreement across methods, where it is impossible to differentiate which source of variability leads to the results observed in this study. Nevertheless, the use of free weights increases the ecological validity of the study as these are commonly used by athletes. Additionally, for the analysis for agreement the force plate was sampled at 200 Hz compared to 1000 Hz used previously [15], which may have influenced the findings. For the aggregated reliability analysis, both 200 Hz and 2000 Hz force plates were used, and we would argue that the findings of reliability seem independent of sampling frequency.

Conclusions and practical applications

A 5–10% between-session CV in jump height is not acceptable for accurately assessing S_{FV} and V_0, regardless of measurement method, using a loading range of bodyweight up to 80 kg (forces ranging from 40–70% of F_0). Caution is advised when using similar protocols for individual training recommendations or interpreting training adaptions for athletes. Efforts should be made to either reduce the variation in jumping performance or to assess loads closer to the FV-intercept. Increasing the loading range can be achieved by using alternative exercises such as a leg press exercise. Reducing the variation in jumping performance may possibly be achieved through additional practice attempts, and attention should be given to the depth of the squatting motion during the vertical jumps. F_0 and P_{max} showed high reliability and generally good agreement across measurement methods, indicating that these variables can be used with confidence by researchers and coaches. However, one should be aware of the poor reliability of the FV-variables V_0 and S_{FV} obtained from vertical jumping, as well as differences across measurement methods for assessing individual FV-relationships.

Supporting information

S1 Dataset.
(XLSX)

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References

1. Colyer SL, Stokes KA, Bilzon JL, Holdcroft D, Salo AI. Training-related changes in force–power profiles: implications for the skeleton start. Int J Sports Physiol Perform. 2018; 13(4):412–419. https://doi.org/10.1123/ijspp.2017-0110 PMID: 28872389
2. Djuric S, Cuk I, Sreckovic S, Mirkov D, Nedeljkovic A, Jaric S. Selective effects of training against weight and inertia on muscle mechanical properties Int J Sports Physiol Perform. 2016; 11(7):927–932. https://doi.org/10.1123/ijspp.2015-0527 PMID: 26788908
3. Jiménez-Reyes P, Samozino P, Brughelli M, Morin J-B. Effectiveness of an individualized training based on force-velocity profiling during jumping. Front Physiol. 2017; 7:677. https://doi.org/10.3389/fphys.2016.00677 PMID: 28119624
4. Samozino P, Rejc E, Di Prampero PE, Belli A, Morin J-B. Optimal force–velocity profile in ballistic movements—altius: citius or fortius? Med Sci Sports Exerc. 2012; 44(2):313–322. https://doi.org/10.1249/MSS.0b013e31822d757a PMID: 21775909
5. Samozino P, Edouard P, Sangnier S, Brughelli M, Gimenez P, Morin J-B. Force-velocity profile: imbalance determination and effect on lower limb ballistic performance. Int J Sports Med. 2014; 35(06):505–510. https://doi.org/10.1055/s-0033-1354382 PMID: 24227123
6. Weakley J, Mann B, Banyard H, McLaren S, Scott T, Garcia-Ramos AJS, et al. Velocity-Based Training: From Theory to Application. Strength & Cond J. 2020. https://doi.org/10.1519/SSC.0000000000000560
7. Alcazar J, Csapo R, Ara I, Alegre LM. On the shape of the force-velocity relationship in skeletal muscles: the linear, the hyperbolic and the double-hyperbolic. Front Physiol. 2019; 10:769. https://doi.org/10.3389/fphys.2019.00769 PMID: 31275173
8. Alcazar J, Pareja-Blanco F, Rodriguez-Lopez C, Navarro-Cruz R, Cornejo-Daza PJ, Ara I, et al. Comparison of linear, hyperbolic and double-hyperbolic models to assess the force-velocity relationship in multi-joint exercises. Eur J Sport Sci. 2020;1–11. https://doi.org/10.1080/17461391.2020.1753816 PMID: 32255757
9. Samozino P. A simple method for measuring lower limb force, velocity and power capabilities during jumping. In Morin J-B, Samozino P, editors, Biomechanics of training and testing., New York, Springer; 2018. pp. 65–96
10. Hopkins WG. Measures of reliability in sports medicine and science. Sports Med. 2000; 30(1):1–15. https://doi.org/10.2165/00007256-200030010-00001 PMID: 10907753
11. Feeney D, Stanhope SJ, Kaminski TW, Machi A, Jaric S. Loaded vertical jumping: force–velocity relationship, work, and power. J Appl Biomech. 2016; 32(2):120–127. https://doi.org/10.1123/jab.2015-0136 PMID: 26398963
12. Meylan CM, Cronin JB, Oliver JL, Hughes MM, Jidovtseff B, Pinder S. The reliability of isoinertial force–velocity–power profiling and maximal strength assessment in youth. Sports Biomech. 2015; 14(1):68–80. https://doi.org/10.1080/14763141.2014.982696 PMID: 25600132
13. Alcazar J, Rodriguez-Lopez C, Ara I, Alfaro-Acha A, Mañas-Bote A, Guadalupe-Grau A, et al. The force-velocity relationship in older people: reliability and validity of a systematic procedure. Int J Sports Med. 2017; 38(14):1097–1104. https://doi.org/10.1055/s-0043-119880 PMID: 29126339
14. Sreckovic S, Cuk I, Djuric S, Nedeljkovic A, Mirkov D, Jaric S. Evaluation of force–velocity and power–velocity relationship of arm muscles. Eur J Appl Physiol. 2015; 115(8):1779–1787. https://doi.org/10.1007/s00421-015-3165-1 PMID: 25828144
15. Jiménez-Reyes P, Samozino P, Pareja-Blanco F, Conceição F, Cuadrado-Peñafiel V, González-Badillo J, et al. Validity of a simple method for measuring force-velocity-power profile in countermovement jump. Int J Sports Physiol Perform. 2017; 12(1):36–43. https://doi.org/10.1123/ijspp.2015-0484 PMID: 27002490

16. Pérez-Castilla A, Piepoli A, Delgado-García G, Garrido-Blanca G, García-Ramos A. Reliability and concurrent validity of seven commercially available devices for the assessment of movement velocity at different intensities during the bench press. J Strength Cond Res. 2019; 33(5):1258–1265. https://doi.org/10.1519/JSC.0000000000003118 PMID: 31034462
17. Janicijevic D, Knezevic OM, Mirkov DM, Pérez-Castilla A, Petrovic M, Samozino P, et al. Assessment of the force-velocity relationship during vertical jumps: influence of the starting position, analysis procedures and number of loads. Eur J Sports Sci. 2019; 20: 614–623. https://doi.org/10.1080/17461391.2019.1645886 PMID: 31314671
18. Janicijevic DN, Knezevic OM, Mirkov DM, Pérez-Castilla A, Petrovic MR, García-Ramos A. Magnitude and reliability of mechanical outputs obtained during loaded squat jumps performed from different knee angles. Sports Biomech. 2019;1–13. https://doi.org/10.1080/14763141.2019.1618390 PMID: 31232220
19. Valenzuela Pedro L. GS-M, Elaia Torrontegi, Javier Vázquez-Carrion, Zigor Montalvo aGGH. Should we base training prescription on the force–velocity profile? exploratory study of its between-day reliability and differences between methods. Int J Sports Physiol Perform. 2020; Forthcoming.
20. Giroux C, Rabita G, Chollet D, Guilhem G. What is the best method for assessing lower limb force-velocity relationship? Int J Sports Med. 2015; 36(02):143–149. https://doi.org/10.1055/s-0034-1385886 PMID: 25259590
21. Padulo J, Migliaccio GM, Ardigò LP, Leban B, Cosso M, Samozino P. Lower limb force, velocity, power capabilities during leg press and squat movements. Int J Sports Med. 2017; 38(14):1083–1089. https://doi.org/10.1055/s-0043-118341 PMID: 29050041
22. García-Ramos A, Pérez-Castilla A, Morales-Artacho AJ, Almeida F, Padial P, Bonitch-Góngora J, et al. Force-velocity relationship in the countermovement jump exercise assessed by different measurement methods. J Hum Kinet. 2019, 67: 37–47. https://doi.org/10.2478/hukin-2018-0085 PMID: 31523305
23. Álvarez JAE, García JPF, Da Conceição FA, Jiménez-Reyes P. Individualized training based on force–velocity profiling during jumping in ballet dancers. Int J Sports Physiol Perform. 2019; 15: 788–794. https://doi.org/10.1123/ijspp.2019-0492 PMID: 31715582
24. Abernethy P, Wilson G, Logan P. Strength and power assessment. Sports Med. 1995; 19(6):401–417. https://doi.org/10.2165/00007256-199519060-00004 PMID: 7676101
25. Cuk I, Markovic M, Nedeljkovic A, Ugarkovic D, Kukolj M, Jaric S. Force–velocity relationship of leg extensors obtained from loaded and unloaded vertical jumps. Eur J Appl Physiol. 2014; 114(8):1703–1714. https://doi.org/10.1007/s00421-014-2901-2 PMID: 24819449
26. García-Ramos A, Pérez-Castilla A, Jaric S. Optimisation of applied loads when using the two-point method for assessing the force-velocity relationship during vertical jumps. Sports Biomech. 2018:1–16. https://doi.org/10.1080/14763141.2018.1545044 PMID: 30540216
27. Chavda S, Bromley T, Jarvis P, Williams S, Bishop C, Turner AN, et al. Force-time characteristics of the countermovement jump: Analyzing the curve in Excel. Strength Cond J. 2018; 40(2):67–77.
28. Pérez-Castilla A, Rojas FJ, García-Ramos A. Reliability and magnitude of loaded countermovement jump performance variables: a technical examination of the jump threshold initiation. Sports Biomech. 2019:1–15. https://doi.org/10.1080/14763141.2019.1682649 PMID: 31711369
29. Pérez-Castilla A, Rojas FJ, García-Ramos A. Assessment of unloaded and loaded squat jump performance with a force platform: Which jump starting threshold provides more reliable outcomes? J Biomech. 2019; 92:19–28. https://doi.org/10.1016/j.jbiomech.2019.05.022 PMID: 31126593
30. Cormie P, McCaulley GO, Triplett NT, McBride JM. Optimal loading for maximal power output during lower-body resistance exercises. Med Sci Sports Exerc. 2007; 39(2):340–349. https://doi.org/10.1249/01.mss.0000246993.71599.bf PMID: 17277599
31. Samozino P, Morin J-B, Hintzy F, Belli A. A simple method for measuring force, velocity and power output during squat jump. J Biomech. 2008; 41(14):2940–2945. https://doi.org/10.1016/j.jbiomech.2008.07.028 PMID: 18789803
32. Hopkins WG. Spreadsheets for analysis of validity and reliability. Sportscience. 2015; 19: 36–42.
33. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41: 3–13. https://doi.org/10.1249/MSS.0b013e31818cb278 PMID: 19092709
34. Cronin JB, Hing RD, McNair PJ. Reliability and validity of a linear position transducer for measuring jump performance. J Strength Cond Res. 2004; 18(3):590–593. https://doi.org/10.1519/1533-4287(2004)18<590:RAVOAL>2.0.CO;2 PMID: 15320688
35. Cormack SJ, Newton RU, McGuigan MR, Doyle TL. Reliability of measures obtained during single and repeated countermovement jumps. Int J Sports Physiol Perform. 2008; 3(2):131–144. https://doi.org/10.1123/ijspp.3.2.131 PMID: 19208922

36. Gathercole R, Sporer B, Stellingwerff T, Sleivert G. Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. Int J Sports Physiol Perform. 2015; 10(1):84–92. https://doi.org/10.1123/ijspp.2013-0413 PMID: 24912201

37. Gathercole RJ, Sporer BC, Stellingwerff T, Sleivert GG. Comparison of the capacity of different jump and sprint field tests to detect neuromuscular fatigue. J Strength Cond Res. 2015; 29(9):2522–2531. https://doi.org/10.1519/JSC.0000000000000912 PMID: 26308829

38. Hopkins WG, Schabort EJ, Hawley JA. Reliability of power in physical performance tests. Sports Med. 2001; 31(3):211–234. https://doi.org/10.2165/00007256-200131030-00005 PMID: 11286357

39. Raastad T, Hallen J. Recovery of skeletal muscle contractility after high- and moderate-intensity strength exercise. Eur J Appl Physiol. 2000; 82(3):206–214. https://doi.org/10.1007/s004210050673 PMID: 10929214

40. Byrne C, Eston R. The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance. J Sports Sci. 2002; 20(5):417–425. https://doi.org/10.1080/026404102317366672 PMID: 12043831

41. Taylor KL, Cronin J, Gill ND, Chapman DW, Sheppard J. Sources of variability in iso-inertial jump assessments. Int J Sports Physiol Perform. 2010; 5(4):546–558. https://doi.org/10.1123/ijspp.5.4.546 PMID: 21266738

42. Zivkovic MZ, Djuric S, Cuk I, Suzovic D, Jaric S. Muscle force-velocity relationships observed in four different functional tests. J Hum Kinet. 2017; 56(1):39–49. https://doi.org/10.1515/hukin-2017-0021 PMID: 28469742

43. García-Ramos A, Feriche B, Pérez-Castilla A, Padial P, Jaric S. Assessment of leg muscles mechanical capacities: Which jump, loading, and variable type provide the most reliable outcomes? Eur J Sports Sci. 2017; 17(6):690–698.

44. Williams KJ, Chapman DW, Phillips EJ, Ball NB. Load-power relationship during a countermovement jump: A joint level analysis. J Strength Cond Res. 2018; 32(4):955–961. https://doi.org/10.1519/JSC.0000000000002432 PMID: 29334580

45. Williams KJ, Chapman DW, Phillips EJ, Ball N. Effects of athlete-dependent traits on joint and system countermovement-jump power. Int J Sports Physiol Perform. 2018; 13(10):1378–1385. https://doi.org/10.1123/ijspp.2018-0050 PMID: 29809056

46. Helland C, Midttun M, Saeland F, Haugvad L, Olstad DS, Solberg PA, et al. A strength-oriented exercise session required more recovery time than a power-oriented exercise session with equal work. PeerJ. 2020; 8:e10044. https://doi.org/10.7717/peerj.10044 PMID: 33062443

47. Williams KJ, Chapman DW, Phillips EJ, Ball NB. Measurement bias in estimates of system power during a vertical jump. Sports Biomech. 2019:1–13. https://doi.org/10.1080/14763141.2019.1649715 PMID: 31573403

48. Lake JP, Lauder MA, Smith NA. Barbell kinematics should not be used to estimate power output applied to the barbell-and-body system center of mass during lower-body resistance exercise. J Strength Cond Res. 2012; 26(5):1302–1307. https://doi.org/10.1519/JSC.0b013e31822e7b48 PMID: 22516904

49. Wade L, Lichtwark GA, Farris DJ. Comparisons of laboratory-based methods to calculate jump height and improvements to the field-based flight-time method. Scand J Med Sci Sports. 2020; 30(1):31–37. https://doi.org/10.1111/sms.13556 PMID: 31544260

50. Attia A, Dhahbi W, Chaouachi A, Padulo J, Wong D, Chamari K. Measurement errors when estimating the vertical jump height with flight time using photocell devices: the example of Optojump. Biol Sport. 2017; 34(1):63–70. https://doi.org/10.5114/biolsport.2017.63735 PMID: 28416900

51. Pérez-Castilla A, García-Ramos A. Evaluation of the most reliable procedure of determining jump height during the loaded countermovement jump exercise: Take-off velocity vs. flight time. J Strength Cond Res. 2018; 32(7):2025–2030. https://doi.org/10.1519/JSC.0000000000002583 PMID: 29570575

52. Mitchell LJ, Argus CK, Taylor K-L, Sheppard JM, Chapman DW. The effect of initial knee angle on concentric-only squat jump performance. Res Q Exerc Sport. 2017; 88(2):184–192. https://doi.org/10.1080/02701367.2017.1293777 PMID: 28339350

53. Cormie P, McBride JM, McCaulley GO. Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. J Strength Cond Res. 2009; 23(1):177–186. https://doi.org/10.1519/JSC.0b013e3181889324 PMID: 19077740

54. Morin J-B, Samozino P. Biomechanics of training and testing: innovative concepts and simple field methods. New York: Springer; 2018.

55. Frost DM, Cronin J, Newton RU. A biomechanical evaluation of resistance. Sports Med. 2010; 40(4):303–326. https://doi.org/10.2165/11319420-000000000-00000 PMID: 20364875

56. Bobbert MF. Why is the force-velocity relationship in leg press tasks quasi-linear rather than hyperbolic? J Appl Physiol. 2012; 112(12):1975–1983. https://doi.org/10.1152/japplphysiol.00787.2011 PMID: 22442026

57. Samozino P, Morin J-B, Hintzy F, Belli AJJoTB. Jumping ability: a theoretical integrative approach. J Theor Biol. 2010; 264(1):11–8. https://doi.org/10.1016/j.jtbi.2010.01.021 PMID: 20109471

58. Garcia-Ramos A, Janicijevic DJI, Science E. Potential benefits of multicenter reliability studies in sports science: A practical guide for its implementation. 2020(Preprint):1–6.

Paper II

Should we individualize training based on force-velocity profiling to improve physical performance in athletes?

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ORIGINAL ARTICLE

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Should we individualize training based on force-velocity profiling to improve physical performance in athletes?

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The present study aimed to examine the effectiveness of an individualized training program based on force-velocity (FV) profiling on jumping, sprinting, strength, and power in athletes. Forty national level team sport athletes (20 ± 4years, 83 ± 13 kg) from ice-hockey, handball, and soccer completed a 10-week training intervention. A theoretical optimal squat jump (SJ)-FV-profile was calculated from SJ with five different loads (0, 20, 40, 60, and 80 kg). Based on their initial FV-profile, athletes were randomized to train toward, away, or irrespective (balanced training) of their initial theoretical optimal FV-profile. The training content was matched between groups in terms of set x repetitions but varied in relative loading to target the different aspects of the FV-profile. The athletes performed 10 and 30 m sprints, SJ and countermovement jump (CMJ), 1 repetition maximum (1RM) squat, and a leg-press power test before and after the intervention. There were no significant group differences for any of the performance measures. Trivial to small changes in 1RM squat (2.9%, 4.6%, and 6.5%), 10 m sprint time (1.0%, −0.9%, and −1.7%), 30 m sprint time (0.9%, −0.6%, and −0.4%), CMJ height (4.3%, 3.1%, and 5.7%), SJ height (4.8%, 3.7%, and 5.7%), and leg-press power (6.7%, 4.2%, and 2.9%) were observed in the groups training toward, away, or irrespective of their initial theoretical optimal FV-profile, respectively. Changes toward the optimal SJ-FV-profile were negatively correlated with changes in SJ height ($r = -0.49$, $p < 0.001$). Changes in SJ-power were positively related to changes in SJ-height ($r = 0.88$, $p < 0.001$) and CMJ-height ($r = 0.32$, $p = 0.044$), but unrelated to changes in 10 m ($r = -0.02$, $p = 0.921$) and 30 m sprint time ($r = -0.01$, $p = 0.974$). The results from this study do not support the efficacy of individualized training based on SJ-FV profiling.

KEYWORDS
jumping, performance, sprinting, strength training

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1 | INTRODUCTION

Force-velocity (FV) profiling has received increasing attention as a tool for individual training prescriptions in athletes.[1-3] Individualizing training based on the FV-profile is founded on the concept of a theoretical optimal FV-profile.[4,5] Samozino et al.[1,2,4] showed that the difference between the theoretical optimal FV-profile and the actual measured FV-profile, termed FV Imbalance (FV_{IMB}), is both theoretically and experimentally related to jumping performance. This means that the theoretical framework can predict athletes jump height based on their FV_{IMB} and FV-maximal power (P_{max}), as well it shows that larger FV Imbalance predicts lower jump heights for a given P_{max}. Individual differences in the measured FV-profile are further hypothesized to reflect underlying neuromuscular properties, and to give valuable information for the design of training programs to improve jumping performance.[2] Recently, several studies have indeed shown that an individualized training program based on FV_{IMB}, targeting the least developed capacity of the participants, is an effective strategy to improve jumping performance.[3,6-8] Specifically, the athletes that have a "force-oriented profile" perform predominantly high-velocity exercises, whereas athletes with "velocity-oriented profiles" perform predominantly high force exercises in their training.[3,6-8] Thereby, improving jumping performance by reducing the athletes individual $FV_{IMB,}$ without changes in P_{max}.

Despite the large increases in jump performance previously observed after FV_{IMB}-individualized training,[3,6-8] a number of questions remain unanswered. Firstly, as shown by several studies, muscular power is a strong predictor for explosive type athletic performance.[9-11] It is unknown if a reduction in the squat jump (SJ)-FV_{IMB} without changes in P_{max} will be advantageous for other relevant performance measures such as countermovement jump (CMJ) and sprinting performance. A shift in the FV-profile, without a concomitant increase in P_{max}, implies that power has decreased either at high or low velocities.[3] This might be problematic if there are several desired performance outcomes or if the desired performance outcome is a complex movement task including power production at both low and high velocities (ie, in sprint running). It is therefore of interest to investigate the effectiveness of such individualized training on multiple performance outcomes that are usually assessed and of interest to coaches, such as CMJ height, maximal strength, 10, 30 m sprint and measures of power in other movements than the SJ.

Additionally, considering the research on responders and non-responders, it can be speculated whether participants that have a especially developed capacity (ie, being force or velocity oriented), possess this quality precisely because they are responding well to this mode of training.[12] An important question is therefore whether some athletes should focus their training on what they already are good at, instead of their weaknesses (ie, opposite to the FV_{IMB} minimization approach). Lastly, not all previous research have found individualized training based on FV-profiling effective, and others have questioned the measurement accuracy of the methods used to obtain the FV-profiles.[13-16] It is therefore crucial to explore the aforementioned unexplored aspects regarding the FV-training approach.

Hence, the present study aimed to (i) examine whether training toward an optimal FV-profile would induce superior increases in SJ and CMJ height, 1RM strength, 10, 30 m sprint and leg-press power compared to participants either focusing on developing their already strong capacity (ie, training further away the optimal FV-profile) or balanced training (irrespective of their initial FV-profile); (ii) explore the association between changes in SJ-power and SJ height, CMJ height, 10 and 30 m sprint time.

We hypothesized that training toward an optimal FV-profile would induce superior increases in SJ height, but not for the other performance measures, compared to the groups training away or irrespective of their FV-profile. Further, we hypothesized that changes in SJ-power would predict changes in CMJ and SJ height, as well as 10 and 30 m sprint time.

2 | MATERIALS AND METHODS

2.1 | Participants

A total of 40 male athletes participated (age 20 ± 4 years; height 184 ± 9 cm; and body mass 83 ± 13 kg). The athletes were national level team sport players in handball (*n* = 14), ice-hockey (*n* = 16), and soccer (*n* = 10). The handball and ice-hockey players were at elite level, and the soccer players at club level. Written informed consent was obtained before participation. The study was approved by the ethical board of the faculty of sport science and physical education at the University of Agder, and the Norwegian Centre for Research Data, and was performed in agreement with the Declaration of Helsinki.

2.2 | Study design

First, all participants were familiarized with testing procedures, followed by a pre-test, a 10-week training period, and thereafter a post-test. The pre-test was performed approximately 1 week before the first training session, whereas the post-test was performed approximately 1 week after the last training session. The athletes performed the testing sessions at the same time of the day (±2 h), at both pre-test and post-test. Each athlete underwent an incremental loading protocol during the SJ to determine their individual FV-profile, theoretical optimal profile, and FV_{IMB} according to Samozino et al.[17] The participants were allocated to the different training groups by stratified randomization based on their baseline FV_{IMB}. More specific, by sorting the participants from the largest to the smallest FV_{IMB}, each 3rd pair were randomized to either conduct heavy strength training, high-velocity strength training, or a combination of these two. The cutoff for FV deficits was set according to the FV-profile in % of optimal: <90% and >110% for force and velocity deficits, and 90%–110% was considered as well-balanced.[3] Consequently, the participants that were randomized to reduce their FV_{IMB} (ie, force deficit participants training heavy strength, velocity deficit participants training high-velocity strength, and well-balanced participants training a combination of these two) were considered as the group training toward their optimal profile. The participants randomized to train to increase their FV_{IMB} (ie, force deficit participants training high-velocity strength, velocity deficit participants training heavy strength, and well-balanced participants training either high velocity or heavy strength training) were considered as the group training away from their optimal profile. The non-optimized balanced training group consisted of the participants who got randomized to balanced heavy and velocity training and having either a force or a velocity deficit at baseline. Consequently, this allocation resulted in the three groups intended to train toward ($n = 9$), away ($n = 20$), or irrespective ($n = 11$) of their initial theoretical optimal FV-profile.

The training program consisted of 2 sessions per week for 10 weeks and are shown in Table 1 and supplementary Tables S1-S3. The sessions were separated by a minimum of 48 h. The training program was inspired by previous research on individualized training based on FV_{IMB}.[3] The force program consisted of mostly exercises with high loads whereas the exercises in the velocity program consisted of exercises with low loads and high velocity. The balanced heavy and velocity program entailed a combination of both types of exercises. All exercises were performed with maximal intentional velocity. Additionally, the sessions were supervised by the research team to ensure proper execution of the programs. The intensity of the heavy exercises was controlled using reps in reserve with rep ranges that corresponded to relative intensity of 70% 1RM and higher.[18] The exercises with lower loads and higher velocities consisted of various jumping exercises with body mass, light loads or unloading using rubber bands.

The athletes got verbal feedback during the sessions from the research assistants and coaches. Additionally, on a select number of sessions (4–5 sessions) the athletes also got objective feedback on some of the explosive exercises using linear transducers.

The study is based on data collected from multiple regional Olympic training and testing centers, where the same equipment and test leaders were constant at each testing center.

2.3 | Testing procedures

All participants were instructed to prepare for the test days as they would for a regular competition in terms of nutrition, hydration, and sleep as well as refrain from

TABLE 1 Training content for the three different training programs

	Exercises	Rep scheme	Load	Weekly sets	Focus	% of sets
Force program	Deadlift, Hip-thrust, Front squat, Squat, Stiff-leg dead lift, Bulgarian split squat, Trapbar, Calf-raises	3–10	1–6 RIR	14	Strength	82%
	Trapbar	5	50–70% 1RM	4	Power	17%
Balanced program	Deadlift, Front squat, Bulgarian split squat, Hip-thrust, Deadlift	3–10	1–6 RIR	13	Strength	46%
	Box jumps, Stair jumps, Single leg stair jumps, Squat jump w/rubber band, Stair jumps, Trapbar jumps	5–10	Negative-50% 1RM	15	Power	54%
Velocity program	Half Squat, Hip-thrust	3–8	1–2 RIR	6	Strength	21%
	Squat jumps, Trapbar jumps, Step up, Squat jump w/rubber band, countermovement jumps, box jumps, Clean Pull, Stair jumps, Single leg stair jumps	5–10	Negative-50% 1RM	22	Power	79%

Abbreviations: RIR, Reps in reserve; 1RM, One repetition maximum; reps, repetitions; Set, training sets.

strenuous exercise 48 h before testing. Testing was performed indoors, and the participants were instructed to use identical footwear and clothing on each test day. Body mass was measured wearing training clothes and shoes. A standardized ~10-min warm-up procedure before testing, consisting of jogging, local muscle warm-up (hamstring and hip mobility), running drills (eg, high knees, skipping, butt-kicks, and explosive lunges), and body mass jumps were performed. Breaks (5–10 min) were given between the different tests to ensure proper recovery. The testing protocol consisted of a series of SJ, CMJ, 30-m sprints, 1RM back-squat, and a leg-press test with incremental loads and in the corresponding order. Ultrasound measurements were performed on either a separate day (during familiarization) or before the physical tests for some of the participants. Reliability of the FV and performance measures has been reported previously.[15]

The SJs were performed with an incremental loading protocol consisting of 0.1, 20, 40, 60, and 80 kg. A broomstick was used as the 0.1 kg load. Two valid trials were registered with each load. Countermovement was verbally forbidden for the SJ and checked visually with the direct force output from the force plate. The recovery time between each attempt was 2–3 min. For the SJ, participants were asked to maintain their individual starting position for about 2 s and then apply force as fast as possible and jump for maximum height before landing with their ankles in an extended position. The starting position for both SJ and CMJ was standardized to the athletes' self-selected starting position and kept constant for all jumps and testing sessions using a rubber band beneath the thighs and visually confirmed by the test leaders. If these requirements were not met, the trial was repeated. The CMJ test was performed with only body mass in the same procedure as SJ, without a pause in the bottom position. All vertical jumps were measured with a force plate (Musclelab; Ergotest AS), obtained from the flight time measures. Rate of force development (RFD) was obtained as the peak derivative within 30 ms from the unloaded SJ force-time measure.[19] The force signal was sampled at 200 Hz and up sampled to 1000 Hz by spline integration using the integrated software. The leg press was performed using a Keiser A300 horizontal leg-press dynamometer (Keiser Sport), and the FV parameters were derived from its software with a 10-repetition FV test with incremental loads based on each participant´s 1RM load (acquired at the familiarization session). The seating position was adjusted for each participant aiming at a vertical femur, equivalent to an 80-90° knee angle, and feet placed with heals at the bottom end of the foot pedal. Participants were asked to extend both legs with maximum effort during the entire 10-repetition FV test. The test started with two practice attempts at the lightest load, corresponding to ~15% of 1RM. Thereafter, the load was gradually increased with fixed steps (~20–30 kgf) for each attempt until reaching the ~1RM load and a total of 10 attempts across the FV curve (15%–100% of 1RM). The rest period between attempts got longer as the load increased. The rest period between attempts was ~10–20 s for the initial five loads, with 20–40 s for the last four rest periods. Due to the pneumatic semi-isotonic resistance, maximal effort does not cause ballistic action, and the entire push-off was performed with maximal intentional velocity. The leg press was performed as a concentric only action without countermovement, as the pedals are resting in their predetermined position prior to each repetition. The eccentric phase was submaximal and not registered. Power from the leg press was then derived from the theoretical maximal power from the FV-profile. For the 30-m sprint, the participants performed 2–4 maximal sprints with 3–5 min of rest between each trial. The timing started when the front foot left the ground and was measured with 5-m intervals using wireless timing gates (Musclelab, Ergotest innovation AS). The trial with the best 30 m time was used for further analysis. The 1RM back-squat was performed using a standardized protocol with incremental loads until 1RM was obtained. Squat depth was standardized to thighs parallel to the ground (top surface of the legs at the hip joint is lower than the top of the knees) and was confirmed visually by the test leaders. The standardized squat depth was kept constant at all testing time points. The increase in load was individual, but constant for each testing session. The minimum increase in load was 2.5 kg, and breaks between attempts were 2–3 min. The heaviest load successfully lifted with the standardized depth was recorded as the participant's 1RM.

2.4 | Data analysis

Average force and average velocity were calculated using two equations considering only simple input variables: body mass, jump height, and push-off distance.[20] A linear regression was fitted to the average force and velocity measurements to calculate the individual FV parameters. F_0 and V_0 are the intercept of the linear regression for the corresponding force and velocity axis. P_{max} is calculated as $F_0 \cdot V_0/4$. The FV-profile in % of optimal and FV_{IMB} was calculated according to Samozino's method.[2] The vertical push-off distance was determined as previously proposed,[21] corresponding to the difference between the extended lower limb length with maximal plantar flexion and the crouch starting position of the jump.

2.5 | Statistical analyses

The sample size was calculated using G*power 3.1.9.2. With a power of 80% and an alpha of 5%, we needed a minimum of 34 participants to detect a significant group difference with an effect size (Cohen's f) of 0.5.[3] One-way ANCOVA was used to analyze between-group differences, with baseline measures as the covariate. Analyses for within group pre-post changes were conducted using a paired sample *t* test. Pearson product-moment correlation coefficient (Pearson *r*) was used to determine the relationships between the FV-variables and the performance measures. Multiple regression analyses were performed to determine how much of the variance in SJ height could be explained by the changes in P_{max} and FV_{IMB}. Standardized effect size (ES) was calculated from the pre-post changes divided by the pooled pre-SD (from all participants) and interpreted categorically as (< 0.20 trivial; 0.20–0.60 small; 0.60–1.20 moderate; 1.20–2.00 large; and >2 extremely large).[22] Means with corresponding variance are presented with SD unless stated otherwise. Confidence limits for all analyses were set at 95% and significance level at <0.05. All statistical analyses were performed using Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA) and IBM statistical package (version 25; SPSS Inc).

3 | RESULTS

All SJ-FV-profiles showed strong linearity at all testing time points ($R^2 = 0.97 \pm 0.01$). The participants completed on average 15 ± 3 out of the 20 scheduled training sessions (75%), with no differences between the groups in terms of attendance (Toward: 14 ± 4, Away: 15 ± 3, and irrespective: 15 ± 2 $p > 0.05$). At baseline, five participants were categorized with a velocity deficit, 20 with a force deficit and 15 as well-balanced. There were no significant differences in FV_{IMB} reduction between the groups training toward (−3 ± 21%), away (−6 ± 15%), or irrespective of their FV-profile (−1 ± 16%) ($p > 0.05$) after the training intervention (Figure 1). Results for the SJ-FV parameters are presented in Table 2, divided by each deficit and training program. There were no significant group differences for changes in any of the performance measures ($F = 0.14$–2.73, $n^2 = 0.01$–0.13, $p = 0.08$–0.87; Figure 2). Results for the post-hoc analysis from the main analysis are presented in Table 3.

Changes in SJ-power were significantly related to changes in SJ-height ($r = 0.88$, $p < 0.001$) and CMJ-height ($r = 0.32$, $p = 0.044$), but unrelated to changes in 10 m ($r = -0.02$, $p = 0.921$) and 30 m sprint time ($r = -0.01$, $p = 0.974$). Further, changes toward the optimal SJ-FV-profile were negatively correlated with changes in SJ height ($r = -0.49$, $p < 0.001$; Figure 3). Multiple linear regressions showed that 88% ($p < 0.001$) of the variance for the change score in SJ height was explained by changes in SJ-P_{max} ($B = 0.81$, $p < 0.001$) FV_{IMB} ($B = 0.13$, $p = 0.004$), body mass ($B = -1.31$, $p < 0.001$), and SJ baseline performance ($B = -0.004$, $p = 0.017$).

Table 4 shows sub-analyses results for each training program (irrespective of FV-training groups) for the performance measures. Participants training the heavy strength

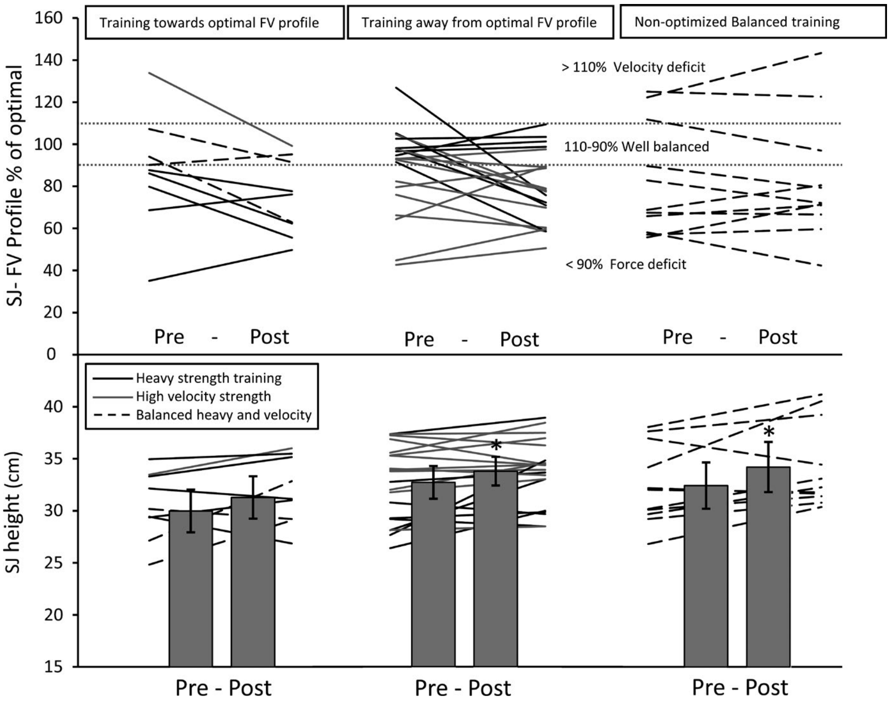

FIGURE 1 The upper panel show individual pre-post changes in the force-velocity (FV) profile expressed as % of optimal between the group training toward, away or irrespective of the FV-profile. The lower panel show individual and pre-post changes in squat jump (SJ) height. Lines represent individual changes in SJ-FV optimal profile and SJ-height. Black lines represent participants training heavy strength, gray lines represent participants training high-velocity strength, and broken lines represent participants training balanced heavy and high-velocity strength. Error bars represent 95% confidence intervals. *$p < 0.05$ pre-post changes

program increased leg press F_0 (5.9 ± 3.7%, $p = 0.01$) and P_{max} (7.7 ± 4.3%, $p = 0.005$), while participants training the high-velocity program did not increase V_0 (2.8 ± 3.0%, $p = 0.09$), and participants training the balanced heavy and velocity program increased P_{max} (3.8 ± 2.6%. $p = 0.01$) but not F_0 (2.3 ± 2.1%, $p = 0.09$) and V_0 (1.6 ± 1.7%, $p = 0.08$).

4 | DISCUSSION

The main finding of the present study was that training toward an optimal SJ-FV-profile was just as effective for improving SJ and CMJ height, 1RM strength, 10 and 30 m sprints, and leg-press power, compared to participants training away

TABLE 2 Results for the SJ-Force-Velocity variables from all subgroups

				Pre	Post	Change
	Deficit	**Training programs**	***n*=**	**Mean ± SD**	**Mean ± SD**	**Δ% ± SD**
Optimal FV (%)	Force	Strength	5	71 ± 22	64 ± 12	−3.4 ± 30.1
		Balanced	8	68 ± 12	68 ± 12	0.6 ± 17.7
		Velocity	7	65 ± 16	68 ± 15	7.8 ± 24.2
	Velocity	Strength	1	127 ± na	76 ± na	−40.3 ± na
		Balanced	3	120 ± 7	121 ± 23	0.7 ± 15.4
		Velocity	1	134 ± na	99 ± na	−25.9 ± na
	No-deficit	Strength	6	97 ± 4	91 ± 20	−6.7 ± 19.8
		Balanced	3	97 ± 9	83 ± 18	−14.1 ± 19.4
		Velocity	6	98 ± 6	82 ± 10	−15.4 ± 13.8
P_{max} (W/kg)	Force	Strength	5	24.9 ± 4.3	24.7 ± 2.2	1.0 ± 13.4
		Balanced	8	25.3 ± 3.1	27.2 ± 3.3	7.8 ± 7.5
		Velocity	7	25.9 ± 4.2	25.4 ± 4.7	−2.0 ± 8.0
	Velocity	Strength	1	24.7 ± na	26.3 ± na	6.4 ± na
		Balanced	3	20.2 ± 2.0	20.8 ± 0.6	3.3 ± 7.2
		Velocity	1	22.2 ± na	23.4 ± na	5.6 ± na
	No-deficit	Strength	6	21.2 ± 2.2	23.0 ± 2.7	9.0 ± 14.3
		Balanced	3	20.0 ± 1.6	23.1 ± 2.1	15.8 ± 12.6
		Velocity	6	21.8 ± 3.1	23.3 ± 2.9	6.8 ± 4.8
F_0 (N/kg)	Force	Strength	5	31.4 ± 2.7	30.2 ± 1.5	−3.3 ± 8.2
		Balanced	8	31.5 ± 2.2	32.4 ± 3.3	2.8 ± 7.1
		Velocity	7	30.4 ± 3.5	30.8 ± 2.8	2.0 ± 8.1
	Velocity	Strength	1	40.7 ± na	32.3 ± na	−20.8 ± na
		Balanced	3	35.5 ± 2.4	36.1 ± 3.7	1.5 ± 6.7
		Velocity	1	39.6 ± na	34.9 ± na	−11.8 ± na
	No-deficit	Strength	6	34.4 ± 3.2	34.2 ± 3.8	−0.7 ± 5.6
		Balanced	3	33.9 ± 0.8	33.3 ± 2.8	−1.8 ± 6.6
		Velocity	6	33.7 ± 3.5	31.6 ± 2.9	−5.8 ± 6.3
V_0 (m/s)	Force	Strength	5	3.2 ± 0.8	3.3 ± 0.3	5.8 ± 21.5
		Balanced	8	3.2 ± 0.3	3.4 ± 0.4	5.8 ± 10.9
		Velocity	7	3.5 ± 0.7	3.3 ± 0.5	−3.0 ± 15.5
	Velocity	Strength	1	2.4 ± na	3.3 ± na	35.3 ± na
		Balanced	3	2.3 ± 0.1	2.3 ± 0.2	2.0 ± 11.7
		Velocity	1	2.2 ± na	2.7 ± na	19.8 ± na
	No-deficit	Strength	6	2.5 ± 0.0	2.7 ± 0.5	10.8 ± 20.5
		Balanced	3	2.4 ± 0.2	2.8 ± 0.5	19.2 ± 21.5
		Velocity	6	2.6 ± 0.2	2.9 ± 0.2	14.1 ± 11.7

(Continues)

TABLE 2 (Continued)

	Deficit	Training programs	*n*=	Pre Mean ± SD	Post Mean ± SD	Change Δ% ± SD
SJ heigth (cm)	Force	Strength	5	31.8 ± 2.4	31.9 ± 3.5	0.2 ± 6.2
		Balanced	8	33.2 ± 3.9	35.4 ± 4.3	6.5 ± 7.1
		Velocity	7	34.4 ± 3.0	34.1 ± 2.7	−0.9 ± 3.7
	Velocity	Strength	1	37.4 ± na	39.0 ± na	4.2 ± na
		Balanced	3	30.3 ± 3.1	31.3 ± 0.8	3.6 ± 8.4
		Velocity	1	33.5 ± na	36.0 ± na	7.6 ± na
	No-deficit	Strength	6	29.6 ± 1.9	31.6 ± 2.6	7.0 ± 11.9
		Balanced	3	27.4 ± 2.7	30.4 ± 2.1	11.7 ± 13.0
		Velocity	6	32.8 ± 3.8	34.6 ± 3.1	5.7 ± 5.2

Note: Mean values are presented with standard deviations (SD). Δ% equals percent change from pre-post ES, Effect size; W, watts; N, Newtons; m/s, Meters per seconds; Cm, Centimeters; Kg, Kilograms. The cutoff for FV deficits was set according to the FV-profile in % of optimal: <90% and >110% for force and velocity deficits, and 90%–110% was considered as No-deficit/well-balanced. Strength program = mostly exercises with low velocity and high loads. Velocity program = mostly exercises with low loads and high velocity. Balanced program = combination of both types of exercises.

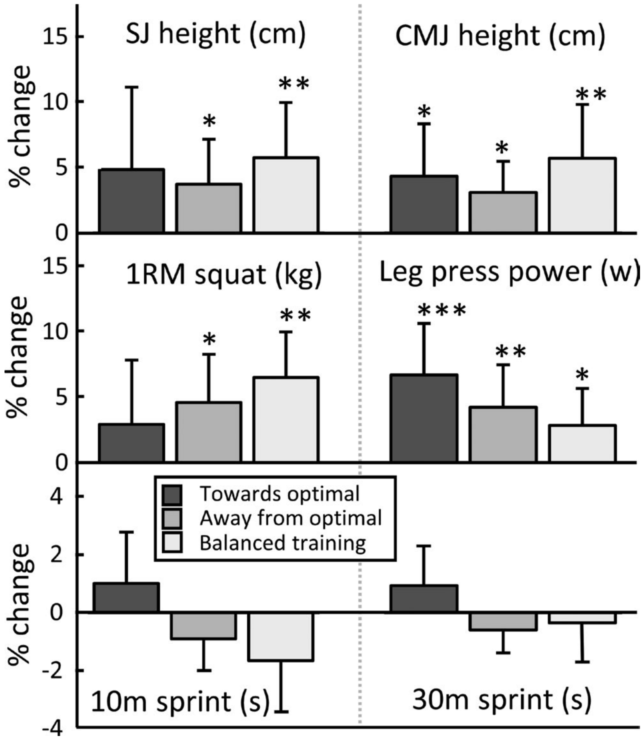

FIGURE 2 Percent change from pre to post in the performance measures in the three groups training toward, away or irrespective (balanced training) of their initial theoretical optimal FV-profile. SJ, Squat jump; CMJ, Countermovement jump; 1RM, one repetition maximum. Kg, Kilograms; S, seconds; Cm, centimeters; and w, watts. Error bars represent 95% confidence intervals. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$

or irrespective of their initial FV-profiles. Additionally, increasing SJ- P_{max} was positively associated with increases in both SJ and CMJ height but not 10 and 30 m sprint times.

To the authors' knowledge, four studies have previously evaluated the effectiveness in individualized training based on FV_{IMB},[3,6-8] which generally have shown small to large effect sizes ranging from 0.37 to 1.45. Contrarily to previous studies, we only observed small improvements in jump height (ES = 0.30–0.50) and no clear differences between groups. The small changes observed could be due the lower training attendance in the present study, where the participants completed ~15 sessions in the 10-week period (compared to 18 sessions[3]). The discrepancy in training effect between the present and previous studies might also be attributed to differences in training status of the participants. Nevertheless, two of the studies were conducted in trained athletes (rugby and soccer), with similar baseline SJ height (33 and 31 cm) to the present study (32 cm).[3,6] Only the study by Simpson et al.,[7] where they included highly trained rugby players (SJ height = 40 cm), showed comparable increases in SJ height (ES = 0.37) as the present study. We should, however, also consider that jump heights were measured by different devices (force plate vs iPhone) in these studies, which could have affected the absolute values.[3,6-8] Furthermore, only two of the studies included a control group performing a non-optimized training regimen for comparison.[3,6-8]

Intriguingly, we were not able to either reduce or increase the FV_{IMB} of the groups training toward or away from their optimal FV-profile. The lack of changes in FV_{IMB} might be due to the large measurement variation in the slope of the FV relationship obtained from vertical jumping (±20%[15]), which is used for the calculation of FV_{IMB}.[2] It is therefore likely that many real changes in FV_{IMB} were smaller than the detection threshold of testing procedure. Nevertheless, despite large measurement variation in FV_{IMB}, the participants were likely allocated

TABLE 3 Results from the main groups, training towards, away, or irrespective of their initial theoretical optimal FV-profile

		Pre	Post	Change		Between group difference (ANCOVA)			
Variables & groups	***n*=**	**Mean ± SD**	**Mean ± SD**	**Δ% ± SD**	**ES ± 95% CI**	**Group**	**Mean**	**95% CI [LB, UB]**	***p*-Value**
1RM squat (kg)									
TOW	9	125.6 ± 19.4	128.6 ± 18.2	2.9 ± 7.5	0.13 ± 1.00	TOW VS AWA	−1.4	[−10.2, 7.3]	0.97
AW	20	123.3 ± 22.8	128.0 ± 21.0	4.6 ± 8.4*	0.20 ± 0.64	TOW VS BAL	−6.4	[−16.3, 3.5]	0.31
BAL	11	134.3 ± 26.8	142.7 ± 27.1	6.5 ± 5.9**	0.36 ± 0.89	BAL VS AWA	−4.9	[−13.3, 3.4]	0.38
10 m sprint (s)									
TOW	9	1.72 ± 0.12	1.74 ± 0.14	1.0 ± 2.7	0.15 ± 1.00	TOW VS AWA	0.04	[−0.011, 0.083]	0.18
AW	20	1.70 ± 0.11	1.69 ± 0.10	−0.9 ± 2.5	−0.14 ± 0.64	TOW VS BAL	0.05	[−0.006, 0.101]	0.09#
BAL	11	1.67 ± 0.14	1.64 ± 0.15	−1.7 ± 3.0	−0.22 ± 0.89	BAL VS AWA	0.01	[−0.033, 0.056]	0.88
30 m sprint (s)									
TOW	9	4.25 ± 0.24	4.29 ± 0.28	0.9 ± 2.1	0.22 ± 1.00	TOW VS AWA	0.07	[−0.021, 0.154]	0.18
AW	20	4.20 ± 0.17	4.17 ± 0.15	−0.6 ± 1.8	−0.14 ± 0.64	TOW VS BAL	0.05	[−0.047, 0.153]	0.48
BAL	11	4.13 ± 0.18	4.11 ± 0.24	−0.4 ± 2.3	−0.07 ± 0.89	BAL VS AWA	−0.01	[−0.097, 0.068]	0.96
SJ height (cm)									
TOW	9	30.5 ± 3.3	31.9 ± 3.2	4.8 ± 9.7	0.37 ± 1.00	TOW VS AWA	−0.3	[−2.6, 2]	0.98
AW	20	32.7 ± 3.6	33.7 ± 3.1	3.7 ± 7.8*	0.30 ± 0.64	TOW VS BAL	−1.0	[−3.5, 1.6]	0.73
BAL	11	32.5 ± 3.8	34.2 ± 4.1	5.7 ± 7.1*	0.50 ± 0.89	BAL VS AWA	−0.7	[−2.8, 1.4]	0.81
CMJ height (cm)									
TOW	9	35.6 ± 3.7	37.0 ± 3.9	4.3 ± 6.2	0.38 ± 1.00	TOW VS AWA	0.1	[−2.2, 2.3]	1.00
AW	20	38.0 ± 3.1	39.1 ± 2.9	3.1 ± 5.4*	0.29 ± 0.64	TOW VS BAL	−0.8	[−3.3, 1.7]	0.80
BAL	11	37.5 ± 5.0	39.5 ± 5.6	5.7 ± 6.9*	0.54 ± 0.89	BAL VS AWA	−0.9	[−2.9, 1.1]	0.62
Leg-press power (W)									
TOW	9	1471 ± 295	1559 ± 261	6.7 ± 6.0**	0.24 ± 1.00	TOW VS AWA	20	[−81.6, 120.7]	0.95
AW	20	1606 ± 354	1666 ± 350	4.2 ± 7.4*	0.17 ± 0.64	TOW VS BAL	22	[−95.2, 139.2]	0.95
BAL	11	1778 ± 425	1826 ± 428	2.9 ± 4.8	0.13 ± 0.89	BAL VS AWA	3	[−93, 98]	1.00
SJ- RFDmax (N/s)									
TOW	9	8400 ± 3279	6992 ± 1687	−9.3 ± 30.9	−0.49 ± 1.00	TOW VS AWA	−168	[−2655, 2319]	1.00
AW	20	7796 ± 2821	6858 ± 2785	−7.3 ± 34.1	−0.33 ± 0.64	TOW VS BAL	−1394	[−4194, 1406]	0.53
BAL	10	8014 ± 2546	8611 ± 2790	8.4 ± 21.7	0.21 ± 0.94	BAL VS AWA	−1226	[−3551, 1098]	0.48

(Continues)

TABLE 3 (Continued)

		Pre	Post	Change		Between group difference (ANCOVA)			
Variables & groups	***n*=**	**Mean ± SD**	**Mean ± SD**	**Δ% ± SD**	**ES ± 95% CI**	**Group**	**Mean**	**95% CI [LB, UB]**	***p*-Value**
Body mass (kg)									
TOW	9	77.9 ± 6.4	78.8 ± 7.2	1.1 ± 1.9	0.07 ± 1.00	TOW VS AWA	0.8	[−1, 2.5]	0.63
AW	20	83.3 ± 14.0	83.1 ± 13.1	−0.1 ± 2.1	−0.01 ± 0.64	TOW VS BAL	0.0	[−1.9, 2]	1.00
BAL	11	86.6 ± 13.5	86.9 ± 12.5	0.6 ± 1.9	0.03 ± 0.89	BAL VS AWA	−0.7	[−2.3, 0.9]	0.60

Note: Mean values are presented with standard deviations (SD). Δ%: percent change from pre-post. *p*-Values for between group differences are obtained from the ANCOVA, post hoc comparison analysis, whereas within group analysis are from paired sample *t* test. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$. †Baseline difference at $p < 0.05$.

Abbreviations: TOW, group training towards optimal force-velocity (FV) profile; AW, group training away from optimal FV-profile; BAL, group training balanced, irrespective of FV-profile; kg, kilogram; s, seconds; cm, centimeters; W, Watts; N/s, Newtons per seconds; mm, millimeters; deg°, Degrees; RFD, Rate of force development.

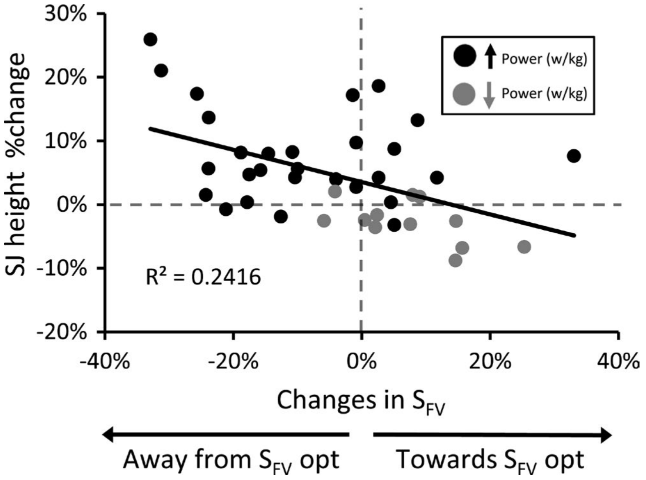

FIGURE 3 The association between changes in squat jump (SJ) height and changes either toward or away from the optimal (opt) force-velocity (FV) profile. The black dots represent increase (>0% change) in SJ relative theoretical maximal power (P_{max}/kg), and the gray dots represent decrease (<0% change) in relative P_{max}. S_{FV}, slope of the force-velocity profile

to their correct groups as evidenced by the larger between vs. within variation (Table 2). Practically speaking, only 11 out of the 40 participants changed "deficit" from pre to post (Figure 1), suggesting that majority of the participants were allocated to the correct group. Further, we would argue that our results indicate that the participants changed their FV-characteristics in the intended direction. This change is not evident in the measures from the SJ-FV-profile, probably due to the measurement variation.[15] However, the results from the less variable leg-press measures (±5%[15]) show that the heavy strength program increased F_0 while the balanced program increased P_{max}. Based on this we could expect similar results as the previous studies.[3,6-8] Moreover, the "optimized" group (training toward optimal profile) showed similar magnitude of increase in jump height (although not statistical significant) as the study by Simpson et al.[7] (ES = 0.37 vs 0.37). As discussed, the effect on jump height might be small compared to other studies due to training status (elite athletes) and a relatively low number of training sessions. Interestingly, both the "away" group and non-optimized balanced group also increased jump height (ES = 0.30 and 0.50, $p < 0.05$, respectively). Contrarily, in the studies of Jiménez-Reyes et al.[3] and Simpson et al.,[7] the balanced ("non-optimized") group did not increase jump height (ES = 0.14 and 0.12). The lack of increase in the "non-optimized" group was attributed to large individual variations in training response due to not targeting the individuals FV_{IMB}.[3] This is highly intriguing, as most previous strength and power training interventions are conducted irrespective of differences in FV-profiles and show generally small to large effect sizes in jump height and power following various resistance

TABLE 4 Results from the sub-groups based on only training programs, irrespective of their initial theoretical optimal FV-profile

		Pre	Post	Change		Between group difference (ANCOVA)			
Variables & groups	***n*=**	**Mean ± SD**	**Mean ± SD**	**Δ% ± SD**	**ES ± 95% CI**	**Group**	**Mean**	**95% CI [LB, UB]**	***p*-Value**
1RM squat (kg)									
Str	12	125.0 ± 26.2	131.7 ± 24.2	6.3 ± 10.2	0.28 ± 0.85	Str vs Bal	4.1	[−4.5, 12.8]	0.56
Bal	14	131.6 ± 24.1	138.6 ± 25.3	5.4 ± 5.7**	0.30 ± 0.78	Str vs Vel	−1.0	[−9.7, 7.7]	0.99
Vel	14	123.6 ± 20.2	126.3 ± 18.1	2.8 ± 6.5	0.11 ± 0.78	Vel vs Bal	−5.2	[−13.5, 3.2]	0.35
10 m sprint (s)									
Str	12	1.70 ± 0.11	1.70 ± 0.12	−0.4 ± 2.5	−0.05 ± 0.85	Str vs Bal	0.01	[−0.04, 0.06]	0.97
Bal	14	1.69 ± 0.14	1.68 ± 0.16	−0.8 ± 3.3	−0.11 ± 0.78	Str vs Vel	0.01	[−0.04, 0.06]	0.98
Vel	14	1.69 ± 0.12	1.68 ± 0.12	−0.8 ± 2.6	−0.11 ± 0.78	Vel vs Bal	0.00	[−0.05, 0.05]	1.00
30 m sprint (s)									
Str	12	4.18 ± 0.17	4.17 ± 0.19	−0.2 ± 1.7	−0.05 ± 0.85	Str vs Bal	0.01	[−0.08, 0.1]	0.98
Bal	14	4.19 ± 0.22	4.19 ± 0.27	0.1 ± 2.5	0.04 ± 0.78	Str vs Vel	−0.02	[−0.11, 0.07]	0.95
Vel	14	4.20 ± 0.18	4.18 ± 0.17	−0.5 ± 2.0	−0.11 ± 0.78	Vel vs Bal	−0.03	[−0.11, 0.06]	0.78
SJ height (cm)									
Str	12	31.2 ± 3.0	32.4 ± 3.5	3.9 ± 9.5	0.33 ± 0.85	Str vs Bal	−0.2	[−2.5, 2.1]	0.99
Bal	14	31.4 ± 4.1	33.4 ± 4.0	7.0 ± 8.5**	0.59 ± 0.78	Str vs Vel	−0.9	[−3.1, 1.2]	0.64
Vel	14	33.7 ± 3.2	34.4 ± 2.7	2.6 ± 5.4	0.22 ± 0.78	Vel vs Bal	−0.7	[−2.9, 1.4]	0.78
CMJ height (cm)									
Str	12	37.3 ± 3.0	38.1 ± 3.4	2.3 ± 6.5	0.21 ± 0.85	Str vs Bal	−0.6	[−2.7, 1.5]	0.87
Bal	14	36.7 ± 5.1	38.8 ± 5.3	6.0 ± 6.6**	0.53 ± 0.78	Str vs Vel	−1.2	[−3.3, 0.9]	0.42
Vel	14	38.0 ± 3.3	39.3 ± 3.1	3.7 ± 4.6**	0.34 ± 0.78	Vel vs Bal	−0.6	[−2.7, 1.4]	0.84
Leg-press power (W)									
Str	12	1489 ± 291	1594 ± 289	7.7 ± 7.7**	0.29 ± 0.85	Str vs Bal	63	[−35.2, 160.2]	0.31
Bal	14	1660 ± 442	1717 ± 435	3.8 ± 4.9*	0.15 ± 0.78	Str vs Vel	41	[−55.5, 138.1]	0.65
Vel	14	1701 ± 347	1735 ± 345	2.3 ± 6.1	0.09 ± 0.78	Vel vs Bal	−21	[−112.6, 70.2]	0.92
SJ- RFDmax (N/s)									
Str	12	8254 ± 3205	6764 ± 1679	−9.7 ± 32.2	−0.52 ± 0.85	Str vs Bal	−123	[−2497, 2250]	1.00
Bal	13	7670 ± 2311	8460 ± 2554	11.4 ± 21.3	0.28 ± 0.81	Str vs Vel	−1682	[−4082, 719]	0.24
Vel	14	8064 ± 3019	6789 ± 3140	−12.6 ± 33.6	−0.45 ± 0.78	Vel vs Bal	−1558	[−3858, 742]	0.27
Body mass (kg)									
Str	12	80.2 ± 8.1	81.3 ± 9.3	1.3 ± 2.0*	0.09 ± 0.85	Str vs Bal	1.7	[0.2, 3.3]	0.03*
Bal	14	83.4 ± 13.5	83.8 ± 12.7	0.7 ± 1.7	0.03 ± 0.78	Str vs Vel	0.6	[−1, 2.1]	0.76
Vel	14	85.0 ± 15.1	84.1 ± 13.7	−0.8 ± 1.9	−0.06 ± 0.78	Vel vs Bal	−1.2	[−2.6, 0.3]	0.16

Note: Mean values are presented with standard deviations (SD). Δ%:percent change from pre-post. *p*-Values for between group differences are obtained from the ANCOVA, post hoc comparison analysis, whereas within group analysis are from paired sample *t*-test. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$. †Baseline difference at $p < 0.05$.

Abbreviations: Str, participants training the heavy strength training program; Vel, participants training low-load high-velocity training; Bal, participants training combination of strength and velocity. Kg, kilogram; s, seconds; cm, centimeters; W, Watts; N/s, Newtons per seconds; mm, millimeters; deg°,**Degrees; RFD, Rate of force development.

and power training regiments.[23-27] It is unclear whether the participants and coaches in the "optimized" and "non-optimized" groups in the studies of Jiménez-Reyes et al. and Simpson et al were aware of their group allocation, which could play an important role for the effectiveness of the training due to a potential nocebo and placebo effect.[28]

Contrary to our hypothesis, we did not observe any difference in SJ height between the groups training toward, away or irrespective of their optimal profile. Nevertheless, a reduction in FV_{IMB} was positively associated with an increase in SJ height when accounting for changes in P_{max}. These results are in accordance with previous research and indicate that reducing FV_{IMB} might be beneficial for increasing SJ height.[3] However, the influence of FV_{IMB} on changes in SJ height was weak ($B = 0.14$) compared to P_{max} ($B = 0.84$). Additionally, a reduction in FV_{IMB} without accounting for changes in P_{max}, was moderately associated with decreases in SJ height (Figure 3), which illustrates the importance of changing P_{max} over FV_{IMB}.

Furthermore, the changes in FV_{IMB} were unrelated to changes in CMJ and sprinting performance, whereas changes in P_{max} were related to changes in CMJ performance. Changes in FV_{IMB} and the slope of the FV-profile, without a concomitant increase in P_{max}, imply that power decrease either at high or at low velocities. Complex sporting movements require power production at a variety of joint angles and contraction speeds, where it probably would be more advantageous with a right shift of the entire FV curve and improve power at both high and low velocities. Moreover, the concept of FV_{IMB} and the existence of an optimal FV-profile assume that individual variations in the FV parameters reflect underlying physiological differences.[2] The first study that experimentally tested the existence of an optimal FV-profile argued that the force dominant participants (rugby players) and velocity dominant participants (soccer players) exhibited their corresponding FV-profile due to their sporting training history.[2] However, a recent investigation of loaded CMJ's has shown that 68% of the variation in the load that maximized power (ie, directly related to the slope of the FV-profile) can be explained by individual variation in strength and anthropometric measures, and was unrelated to training history.[29] Similarly, the study by Jiménez-Reyes, Samozino, Brughelli, and Morin[3] showed clear anthropometric differences in the participants classified with either force deficit (body mass 72.7 ± 8.3 kg, body height 1.78 ± 0.06 m) or velocity deficit (body mass 80.6 ± 9.6 kg, body height 1.81 ± 0.04 m); interestingly, where changes in body mass were not reported. Although several studies have shown the influence of specific training on the FV-profile,[30-34] it is of great relevance to elucidate how much of differences in the slope of FV-profiles obtained from multi-joint movements (thereby FV_{IMB}) that reflect differences in intrinsic physiological characteristics.

Regarding the training effects of the specific programs, it appears that the heavy strength and balanced training programs induced the expected adaptations, that is, improved in 1RM and leg-press power, consistent with the literature.[32,33,35-37] However, the high-velocity program had no clear changes in RFDmax or V_0 in the leg press. The exercises in the velocity program consisted of light loads and high-velocity actions with comparable training volume as previous investigations.[3] However, it can be speculated whether the participants were accustomed to high-velocity movements from their respective sports, and thereby did not receiving sufficient stimuli for velocity-related adaptations.[38] Previous studies that have compared light load training with heavy or combined load training generally show larger adaptations in the force part vs the velocity part of the FV curve.[30-34,38] Hence, it is possible that heavy loading induces a more potent stimulus, and/or there are larger potential for adaptation in force-generating capacities at slow velocities compared to high velocities.[38] Interestingly and consistent with the present study, participants training with a combination of heavy and light loads tend to show greater increases in power across the entire FV curve compared to training with either heavy or light loads.[30-34]

The present study included a large sample of highly trained athletes from handball, soccer, and ice-hockey. The training included experienced coaches with close follow-up during the sessions. Although the study was conducted as a multicenter study, the same test leaders and equipment were used across the different centers. Unfortunately, most participants were categorized as velocity dominated, or well-balanced which caused an uneven allocation between groups. Additionally, the stratified randomization to three different training programs led to an over-allocation to the AW group. This uneven allocation led to smaller statistical power compared to what was calculated in one of the groups. Consequently, comparisons across smaller subgroups such as different training programs within different deficits are not possible. Additionality, due to the lower statistical power, we used three categories for FV deficits, compared to 5 groups used in previous investigations.[3,6-8]

Training toward an optimal SJ-FV-profile did not show favorable effects in SJ height, CMJ height, 10 and 30 m sprint time, 1RM strength or leg-press power compared to participants either training away from their optimal profile or balanced training irrespective of their initial FV-profile. Increasing SJ- P_{max} was positively associated with increases in both SJ and CMJ height but not with 10 and 30 m sprint times. The results from this study do not support the efficacy of individualized training based on FV profiling.

5 | PERSPECTIVE

The present study questions the proposed use of FV-profiles to guide training prescriptions in athletes and rather suggests that power should be prioritized over reducing a theoretical FV Imbalance. It seems to be important to work on shifting the entire FV curve to the right, improving power across the entire FV-continuum, regardless of initial FV-profiles.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

1. Samozino P, Rejc E, Di Prampero PE, Belli A, Morin J-B. Optimal force–velocity profile in ballistic movements—Altius. *Med Sci Sports Exerc*. 2012;44(2):313-322.
2. Samozino P, Edouard P, Sangnier S, Brughelli M, Gimenez P, Morin J-B. Force-velocity profile: imbalance determination and effect on lower limb ballistic performance. *Int J Sports Med*. 2014;35(06):505-510.
3. Jiménez-Reyes SP, Brughelli M, Morin J-B. Effectiveness of an individualized training based on force-velocity profiling during jumping. *Front Physiol*. 2017;7:677.
4. Samozino P, Morin J-B, Hintzy F, Belli A. Jumping ability: a theoretical integrative approach. *J Theor Biol*. 2010;264(1):11-18.
5. Samozino P, Rejc E, Di Prampero PE, Belli A, Morin J-B.Optimal force–velocity profile in ballistic movements-altius: citius or fortius? *Med Sci Sports Exerc*. 2012;44(2):313-322.
6. Jiménez-Reyes P, Samozino P, Morin J-B. Optimized training for jumping performance using the force-velocity imbalance: individual adaptation kinetics. *PLoS One*. 2019;14(5):e0216681.
7. Simpson A, Waldron M, Cushion E, Tallent J. Optimised force-velocity training during pre-season enhances physical performance in professional rugby league players. *J Sports Sci*. 2020;39(1):91–100.
8. Álvarez JAE, García JPF, Da Conceição FA, Jiménez-Reyes P. Individualized training based on force-velocity profiling during jumping in ballet dancers. *Int J Sports Physiol Perform*. 2019;1(aop):1-7.
9. Morris CG, Weber JA, Netto KJ. Relationship between mechanical effectiveness in sprint running and force-velocity characteristics of a countermovement jump in Australian rules football athletes. *J Strength Cond Res*. 2020. https://org.doi/10.1519/JSC.0000000000003583
10. Sleivert G, Taingahue M. The relationship between maximal jump-squat power and sprint acceleration in athletes. *Eur J Appl Physiol*. 2004;91(1):46-52.
11. Harris NK, Cronin JB, Hopkins WG, Hansen KT. Relationship between sprint times and the strength/power outputs of a machine squat jump. *J Strength Cond Res*. 2008;22(3):691-698.
12. Mangine GT, Gonzalez AM, Townsend JR, et al. Influence of baseline muscle strength and size measures on training adaptations in resistance-trained men. *Int J Exerc Sci*. 2018;11(4):198.
13. Valenzuela PL, Sánchez-Martínez G, Torrontegi E, Vázquez-Carrión J, Montalvo Z, Haff GG. Should we base training prescription on the force-velocity profile? Exploratory study of its between-day reliability and differences between methods. *Int J Sports Physiol Perform*. 2021;1(aop):1–7.
14. Rakovic E, Paulsen G, Helland C, Eriksrud O, Haugen T. The effect of individualised sprint training in elite female team sport athletes: a pilot study. *J Sports Sci*. 2018;36(24):2802-2808.
15. Lindberg K, Solberg P, Bjørnsen T, et al. Force-velocity profiling in athletes: reliability and agreement across methods. *PLoS One*. 2021;16(2):e0245791.
16. Šarabon N, Kozinc Ž, Ramos AG, Knežević OM, Čoh M, Mirkov DM. Reliability of sprint force-velocity-power profiles obtained with KiSprint system. *J Sports Sci Med*. 2021;20(2):357-364.
17. Samozino P, Di Prampero PE, Belli A, Morin JB. Optimal force-velocity profile in ballistic movements–altius: citius or fortius? *Med Sci Sports Exerc*. 2012;44(2):313-322. https://doi.org/10.1249/MSS.0b013e31822d757a.
18. Helms ER, Cronin J, Storey A, Zourdos MC. Application of the repetitions in reserve-based rating of perceived exertion scale for resistance training. *Strength Cond J*. 2016;38(4):42.
19. McLellan CP, Lovell DI, Gass GC. The role of rate of force development on vertical jump performance. *J Strength Cond Res*. 2011;25(2):379-385.
20. Samozino P, Morin J-B, Hintzy F, Belli A. A simple method for measuring force, velocity and power output during squat jump. *J Biomech*. 2008;41(14):-2945.
21. Samozino P. A simple method for measuring lower limb force, velocity and power capabilities during jumping. In: Morin JB, Samozino P (Eds.), *Biomechanics of Training and Testing*. Springer. 2018;65-96.
22. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *LWW*. 2009;41(1):3-12.
23. Slimani M, Paravlic A, Granacher U. A meta-analysis to determine strength training related dose-response relationships for lower-limb muscle power development in young athletes. *Front Physiol*. 2018;9:1155.
24. Lesinski M, Prieske O, Granacher U. Effects and dose–response relationships of resistance training on physical performance in youth athletes: a systematic review and meta-analysis. *Br J Sports Med*. 2016;50(13):781-795.
25. Stojanović E, Ristić V, McMaster DT, Milanović Z. Effect of plyometric training on vertical jump performance in female athletes: a systematic review and meta-analysis. *Sports Med*. 2017;47(5):975-986.
26. Hackett D, Davies T, Soomro N, Halaki M. Olympic weightlifting training improves vertical jump height in sportspeople: a systematic review with meta-analysis. *Br J Sports Med*. 2016;50(14):865-872.
27. Markovic G. Does plyometric training improve vertical jump height? A meta-analytical review. *Br J Sports Med*. 2007;41(6):349-355.
28. Beedie C, Benedetti F, Barbiani D, et al. Consensus statement on placebo effects in sports and exercise: The need for conceptual clarity, methodological rigour, and the elucidation of neurobiological mechanisms. *Eur J Sport Sci*. 2018;18(10):1383-1389.

29. Williams KJ, Chapman DW, Phillips EJ, Ball N. Effects of athlete-dependent traits on joint and system countermovement-jump power. *Int J Sports Physiol Perform*. 2018;13(10):1378-1385.
30. Cormie P, McCaulley GO, McBride JM. Power versus strength-power jump squat training. *Med Sci Sports Exerc*. 2007;39(6):996-1003.
31. Cormie P, McGuigan MR, Newton RU. Adaptations in athletic performance after ballistic power versus strength training. *Med Sci Sports Exerc*. 2010;42(8):1582-1598.
32. Toji H, Suei K, Kaneko M. Effects of combined training loads on relations among force, velocity, and power development. *Can J Appl Physiol*. 1997;22(4):328-336.
33. Toji H, Kaneko M. Effect of multiple-load training on the force-velocity relationship. *J Strength Cond Res*. 2004;18(4):792-795.
34. Moss B, Refsnes P, Abildgaard A, Nicolaysen K, Jensen J. Effects of maximal effort strength training with different loads on dynamic strength, cross-sectional area, load-power and load-velocity relationships. *Eur J Appl Physiol Occup Physiol*. 1997;75(3):193-199.
35. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol*. 2002;93(4):1318-1326.
36. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol*. 2007;102(1):368-373.
37. Kaneko M, Fuchimoto T, Toji H, Suei K. Training effect of different loads on the force-velocity relationship and mechanical power output in human muscle. *Scand J Sports Sci*. 1983;5(2):50-55.
38. Crewther B, Cronin J, Keogh J. Possible stimuli for strength and power adaptation. *Sports Med*. 2005;35(11):967-989.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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Paper III

The effects of being told you are in the intervention group on training results: A pilot study

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The effects of being told you are in the intervention group on training results: a pilot study

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Little is known about the placebo effects when comparing training interventions. Consequently, we investigated whether subjects being told they are in the intervention group get better training results compared to subjects being told they are in a control group. Forty athletes (male: n = 31, female: n = 9) completed a 10-week training intervention (age: 22 ± 4 years, height: 183 ± 10 cm, and body mass: 84 ± 15 kg). After randomization, the participants were either told that the training program they got was individualized based on their force–velocity profile (Placebo), or that they were in the control group (Control). However, both groups were doing the same workouts. Measurements included countermovement jump (CMJ), 20-m sprint, one-repetition maximum (1RM) back-squat, a leg-press test, ultrasonography of muscle-thickness (m. rectus femoris), and a questionnaire (Stanford Expectations of Treatment Scale) (Younger et al. in Clin Trials 9(6):767–776, 2012). Placebo increased 1RM squat more than Control (5.7 ± 6.4% vs 0.9 ± 6.9%, [0.26 vs 0.02 Effect Size], Bayes Factor: 5.1 [BF_{10}], p = 0.025). Placebo had slightly higher adherence compared to control (82 ± 18% vs 72 ± 13%, BF_{10}: 2.0, p = 0.08). Importantly, the difference in the 1RM squat was significant after controlling for adherence (p = 0.013). No significant differences were observed in the other measurements. The results suggest that the placebo effect may be meaningful in sports and exercise training interventions. It is possible that ineffective training interventions will go unquestioned in the absence of placebo-controlled trials.

The placebo effect describes a favorable outcome that occurs because of one's belief or expectation that one has received a positive intervention[2]. Given the prevalence of placebo effects, researchers across a wide range of disciplines have attempted to control them for nearly 80 years, with the first placebo-controlled clinical trial published in 1944[3,4]. Similarly, over the last two decades, research in sport and exercise science has shown that placebo and nocebo effects can have a major impact on athletic performance[5].

Notably, studies investigating the placebo effect in sports science are conducted with placebo dietary supplements such as caffeine, creatine monohydrate, carbohydrate, and even anabolic steroids[6]. When the treatment is administered in the form of tablets, injections, capsules, or other comparable forms, studying the effects of a placebo is relatively simple[6]. However, from medicine, we know that the effectiveness of placebos can vary with the administration form[7]. For example, sham surgeries have been shown to induce very strong placebo effects[7], and placebo injections exhibit stronger effects than placebo pills[8]. Following recent advances in placebo research, several forms of interventions have indeed been challenged due to the possibility of strong placebo effects being present[3]. In sports science, we are frequently comparing the efficacy of different resistance training interventions (e.g. comparing exercise selection, loading schemes, frequency, or volume), where it is very difficult to control for the placebo effect[5]. Consequently, it is likely that previous research findings in sport and exercise science are confounded by placebos[5]. As noted by several authors, most training interventions are unable to administer placebos due to obvious reasons such as blinding (i.e., we cannot tell subjects that they are lifting weights 3 days a week, if they are indeed lifting 6 days a week)[2,5,6]. More importantly, most previous training studies do not

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mention nor control for the participant's or researchers' expectations towards the treatment[2,5,6]. It is well known that the researcher's and/or participants' expectations of the intervention can have a major impact on the study's outcome[9–11]. As a result, it is probable that the advocates/inventors of new training approaches will find the efficacy of such concepts to be slightly more effective because of placebo effects[9–11].

A recent popular training concept within sports science is training according to participants' individual "force–velocity" (FV) profiles. Briefly, the individualized training is theorized to work by changing athletes' force–velocity profiles towards a theoretical optimal profile[12]. In practice, athletes with a "force-oriented profile" (i.e., velocity deficit) are commonly prescribed training with a focus on high-velocity exercises, whereas athletes with "velocity-oriented profiles" (i.e., force deficit) get prescribed high-force exercises. Athletes with a "well-balanced" profile, then get training prescriptions with a balanced combination of both high-force and high-velocity training[13–20]. When training according to the FV profiles, the subjects get "individualized" training based on a performance test. The performance test that determines which form of training is "optimal" is a "black box" for the participants, which makes it a perfect setup to investigate the placebo effect (i.e., participants can easily be randomized and told they get optimal or control training without knowing which is actually "optimal")[13–20]. Therefore, in practice, two participants can be doing the exact same workouts, but it is "optimal" for one subject and "non-optimal" for another. The concept is found to be highly effective in some studies, while other studies have yielded different findings[13–20].

Currently, we know very little about the potential placebo effect when investigating different training configurations (e.g., exercise selection, loading, volume, frequency). Hence, the present study aimed to investigate whether a placebo effect is present when participants are told they get "optimal training" compared to being told they get generic "control training".

Methods

Experimental design and participants. Seventy-one athletes were recruited for the study. The participants first completed baseline assessments; a 10-week training intervention followed by post-intervention tests. Due to the Covid-19 pandemic, multiple participants either got sick or quarantined during the study period and were unable to either complete the intervention/or testing sessions. Details regarding the number of dropouts in each group are presented in the CONSORT diagram. Additionally, group comparisons for the dropouts are presented in the results section. The adherence to the training program is also reported in the results section. The number of participants referred to throughout the manuscript is the participants completing the training intervention and pre- and post-testing (n = 40). The athletes were national and club level team sport players in handball (males, n = 31), and soccer (females n = 9), with an average age of 22 ± 4 years, height of 183 ± 10 cm, and body mass of 84 ± 15 kg. The data were collected from multiple regional Olympic training and testing centers. Prior to participation, written informed consent was obtained. The study was approved by the ethical board of the University of Agder's faculty of health and sports science, as well as the Norwegian Centre for Research Data, and was carried out in accordance with the Declaration of Helsinki (except pre-registration). The subjects had to be healthy and not taking any medication that could interfere with the study. All subjects had to be familiar with strength training with a minimum of 6 month of practice. Due to the relatively small sample size, the present study should be considered a pilot study.

The participants were first randomly assigned to one of two groups, Placebo, or Control. In each of these groups, they were again randomized to either a generic power training program or an individualized training program based on their individual force–velocity profile. See Fig. 1 for study design illustration.

Administration of placebo. To administer the placebo treatment, the participants were either told that the training program they got was individualized based on their force–velocity profile, or that they were in the control group. This means, that both groups consisted of subjects doing the same workouts, but half of them believed they did optimal individualized training (Placebo), and the other half believed they were the control group with non-optimal generic training (Control) (Fig. 1). Importantly, as the baseline FV profiles were calculated by a researcher that did not participate in testing or training of the athletes, the FV profile was unknown to the participants and researchers involved in measurements and training. Therefore, administration of the Placebo was possible by telling some of the subjects they have another profile than what is measured. For example, subjects in the Placebo group who got the "force focused training", were all told their FV profiles were velocity-oriented (force "deficit"), and that heavy load training was the optimal training for them. In contrast, participants in the Control group did not receive any information regarding their FV profiles. They were told that they were in the control group, and that the training program they received was developed to improve performance without individualizing based on FV-profiles. All the participants got these instructions verbally as well as in written format. The training programs and exact instructions given to the participants are added as supplementary material (Supplementary material 1). An overview of the training program is presented in Table 1. The training sessions were not supervised by the research team. Exercises were performed in the order they are written in the supplementary Tables.

Testing procedures. All subjects were told to prepare for the test days in the same way as for a regular competition in terms of nutrition, hydration, and sleep, and to avoid excessive exercise 48 h before the test. Before testing, participants completed a standardized 10-min warm-up that included jogging, local muscle warm-up (hamstring and hip mobility), running drills (such as high knees, skipping, butt-kicks, and explosive lunges), and body mass jumps. The testing protocol included a series of countermovement jumps (CMJ's) with incremental loads, 20-m sprints, 1RM back-squat, and leg-press tests. All the subjects were provided with verbal encouragement and instructions to help them do their very best on the performance tests. It is however important to

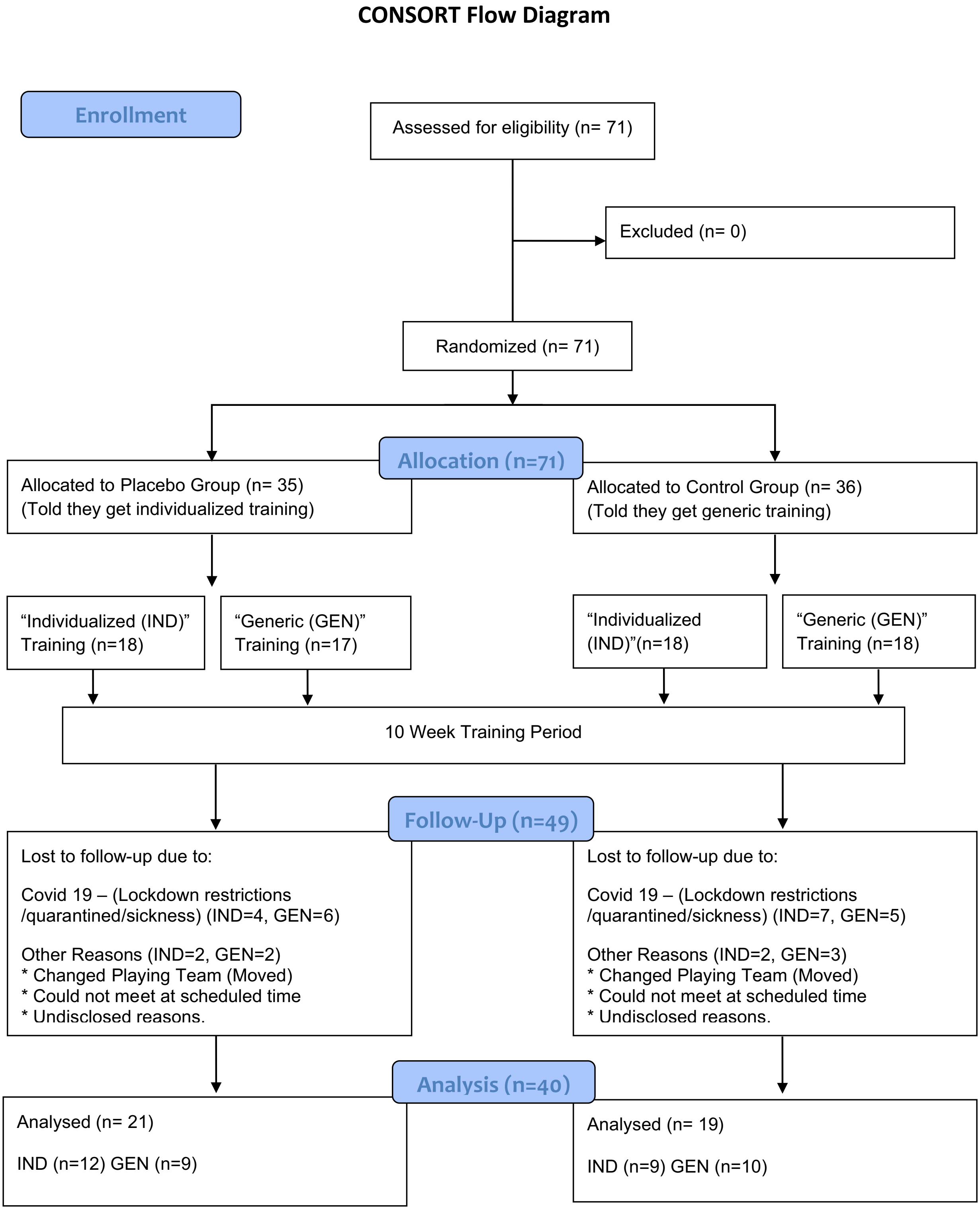

Figure 1. Flow chart of the study design.

note that during the testing, neither the individuals nor the people in charge of the test were aware of the group allocation. Ultrasound measures were taken before the physical testing, or on a separate test day for some of the participants.

The ultrasound measurements were conducted using a brightness mode (B-mode) ultrasonography device (Telemed ArtUS EXT-1H, IT, 70 Hz, Vilnius, Lithuania, EU) using a 60-mm probe (LV8-5N60-A2) measuring resting muscle thickness of m. rectus femoris. All participants lay supine on an examination bench with knees fully extended. The measurement was taken at ~40% from the lateral epicondyle of the knee to the great

	Exercises	Rep scheme	Load	Weekly sets	Focus	% of sets
Force program	Deadlift, Hip-thrust, Front squat, Squat, Stiff-leg dead lift, Bulgarian split squat, Trapbar Deadlift, Calf-raises	3–10	1–6 RIR	14	Strength	82
	Trapbar Deadlift	5	50–70% 1RM	4	Power	18
Balanced program	Deadlift, Front squat, Bulgarian split squat, Hip-thrust, Deadlift	3–10	1–6 RIR	13	Strength	46
	Box jumps, Stair jumps, Single leg stair jumps, Squat jump w/rubber band, Stair jumps, Trapbar jumps	5–10	Negative-50% 1RM	15	Power	54
Velocity program	Half Squat, Hip-thrust	3–8	1–2 RIR	6	Strength	21
	Squat jumps, Trapbar jumps, Step up, Squat jump w/rubber band, countermovement jumps, box jumps, Clean Pull, Stair jumps, Single leg stair jumps	5–10	Negative-50% 1RM	22	Power	79

Table 1. Training content for the 3 different training programs. *RIR* reps in reserve, *1RM* one repetition maximum, *reps* repetitions, *Set* training sets.

trochanter major[20]. Ultrasound settings (Gain, frequency, depth) were optimized for each subject and kept constant at each test session, to best highlight collagenous tissue that constitutes muscle aponeuroses and surrounds muscle fascicles. A transparent sheet was used to record the scanning location relative to natural landmarks such as scars, moles, birthmarks etc. All ultrasound pictures were analyzed using ImageJ (version 1.46r, National Institutes of Health, USA), in a blinded manner (i.e. not the same examiner who took the pictures, and also blinded for the group allocation). The ultrasound measures were taken from 1 picture per subject. Based on pilot testing, we found this procedure to have < 3% test–retest variation.

A modified version of the Stanford Expectations of Treatment Scale (SETS) was utilized to examine expectancy effects. The SETS scale is a previously validated tool for assessing positive and negative treatment expectations in clinical trials[1]. The questionnaire was translated to Norwegian where some of the questions were excluded to make it easier to administer to the participants. All the questionnaires collected from the participants were double-checked to see if any were missing or incomplete. Those that were left blank, patterned, or all marked the same choice, were excluded from the analyses (< 3% of answers). Each participant was instructed to take note of each completed training session to control adherence to the training program. At the post-test—the participant reported their number of completed sessions together with the SETS questionnaire[1]. In accordance with previous research, the adherence was then reported as percentages (i.e., % completed sessions of scheduled sessions).

The CMJ's were performed with an incremental loading protocol of 3 loads, starting at bodyweight, increasing to 40 kg, and the last load was individually adjusted with a goal of jumping approximately 10 cm (range 60–90 kg). The subjects performed 2–3 jumps × 2 for the bodyweight and 40 kg condition and 1–2 jumps × 2 for the heaviest load. The rest between jumps within sets were approximately 10–20 s and about 2–3 min between sets and loads. For all the jumps, the CMJ- depth was standardized to the athletes' self-selected starting position, controlled visually and by the displacement output from the force-plate software. The jump height was measured with a force plate sampling at 1000 Hz (AMTI; Advanced Mechanical Technology, Inc, Waltham Street, Watertown, USA or; Kistler 9286B force plate, Kistler Instruments AG) and calculated from the impulse. The average of the best two trials for each jump condition were used for further analysis. To calculate the actual and optimal FV profile, the proposed methods of Samozino et al.[12] were used. Based on the jump height, body mass, and push-off distance of the subjects, average force and velocity were obtained. Followingly, a linear regression was fitted to the average force and velocity values, where Samozino's method was used to calculate the theoretical optimal FV profile[12]. The difference between the extended lower limb length with maximal plantar flexion and the crouch starting position of the jump was used to calculate the vertical push-off distance, as previously proposed[12]. The bodyweight of the subjects were measured from the steady stance at the force plate.

The participants performed 2–4 maximal sprints of 20-m, with 3–5 min of recovery in between each trial. The timing began when the front foot left the ground and was measured using wireless timing gates at 5-m intervals (Musclelab, Ergotest innovation AS, Langesund, Norway). For subsequent analysis, the best 20-m time was used.

The leg press was performed on a Keiser A300 horizontal leg-press dynamometer (Keiser Sport, Fresno, CA). The FV variables were determined using a 10-repetition FV test with incremental loads based on each participant's estimated 1RM load. The estimation of the 1RM load is based on the test leader's subjective judgment and is considered to be a reliable method for accurately acquiring a FV-profile[21]. Each participant's seating posture was modified to achieve a vertical femur, which corresponded to an 80°–90° knee angle, and feet were placed with heals at the bottom end of the foot pedal. Throughout the 10-repetition FV test, participants were required to extend both legs with maximal effort. The test began with two practice attempts at the lightest load, corresponding to 15% of 1RM. As the load increased, the rest period between attempts increases. For the first five loads, the rest time was 10–20 s, while the last four rest periods were 20–40 s. Because the pedals were resting in their predetermined position before each repetition, the leg press was executed as a concentric-only action with no countermovement. The eccentric phase was not registered. The theoretical maximum power from the FV-profile was then used to calculate leg press power.

The 1RM back-squat was obtained using a standardized protocol, with incremental loading until 1RM was attained. Submaximal squats with 2–4 repetitions at 50% and 60% of 1RM were conducted as part of a brief warm-up, following one repetition at 80%, 90%, and 95% of 1RM (self-estimated at the first time-point). The participants were then given 2–3 trials at the 1RM load with a rest period after each attempt of 2–3 min. The minimum load increase was 2.5 kg and the heaviest load (in kg) successfully lifted with the standardized depth was recorded as the participant's 1RM. The test leaders visually validated that the squat depth was standardized to thighs parallel to the ground (the top surface of the legs at the hip joint is lower than the top of the knees). At all times during the study, the standardized squat depth was maintained[22]. The relative 1RM value (kg/bw) was used for further analysis, as this is closer related to common measures of athletic performance[23].

Statistical analyses. In combination with traditional null-hypothesis testing, a Bayesian approach was used because it is less dependent on sample size, compared with traditional p-values[24,25]. Given our multicenter study design, where the sample size for some of the measures was lower, a Bayesian approach was regarded as more robust[24,25]. The data were checked for normal distribution using the Shapiro–Wilk test before analysis. An independent sample *t* test was conducted to examine the differences between placebo and control groups for all the included measures, in addition to baseline differences between groups. Only the variables from the SETS scale were found to be non-normally distributed and is presented as median and quartiles and differences between groups were analyzed with a rank-biserial coefficient of correlation for the upper and lower quartiles. Additionally, an ANCOVA was conducted to control for potential confounding effects from the expectancy measures and the adherence of the subjects. A paired sample *t* test was used to examine changes within groups before and after the intervention. The standardized effect size (ES) was computed by dividing the pre-post changes by the pooled pre-SD (from all participants) and was categorized as (0.20–0.60 small; 0.60–1.20 moderate; 1.20–2.00 large; > 2 extremely large). Unless otherwise stated, means with the corresponding variance are shown with standard deviation (SD). The interpretation of the Bayes factor (BF_{10}) follows the scale proposed by Jeffreys[26] (1–3 anecdotal; 3–10 substantial; 10–30 strong; 30–100 very strong and > 100 decisive evidence for H_1, whereas $BF_{10} < 1$ suggests support for H_0). The significance level was set at 0.05 and the confidence level were set at 95% for all analyses. Statistical analyses were conducted using JASP version 0.14 (JASP 2020).

Results

There were no significant baseline differences in any of the performance measures, between the placebo and control group (Table 2). There were no difference in age of the subjects between the two groups (Placebo: 22 ± 4y, Control: 22 ± 5y, p = 0.83). Further, there were no significant difference at baseline between the subjects that dropped out vs the subjects who completed the entire study.

Placebo increased 1RM squat more than Control (5.7 ± 6.4% vs 0.9 ± 6.9%, Bayes Factor: 5.1 [BF_{10}], p = 0.025). Additionally, Placebo increased muscle-thickness compared to baseline (3.3 ± 6.1%, BF_{10}: 3.0, p = 0.06), whereas there was no change from baseline in Control (− 1.9 ± 14.0%, BF_{10}: 0.3, p = 0.89). Placebo had slightly higher adherence compared to the control group (placebo: 82 ± 18% control: 72 ± 13%, difference: BF_{10}: 2.0, p = 0.08) (Fig. 2). The group difference in 1RM squat were significant after adjusting for adherence (F = 7.1, $n^2 = 0.19$, p = 0.013), and the SETS expectation level (F = 5.4, $n^2 = 0.16$, p = 0.027).

No significant differences between groups were observed in CMJ, 20-m sprints or leg press power (Table 2). The expectations towards the intervention showed a moderate correlation with the adherence to the training (r = 0.39, BF_{10}: 3.8, p = 0.013). Both groups reported similar median levels of expectations towards the interventions (Placebo: 5.6 ± 0.7 Control: 5.9 ± 1.1 [median and quartiles]). However, the expectations were not-normal

	Pre	Post	Change		Group difference			
Variable and group	**Mean ± SD**	**Mean ± SD**	**Δ ± SD**	**ES**	**Mean ± 95% CI**	**ES**	**BF_{10}**	**p-value**
1RM squat (kg/bw)								
Placebo (PLA)	1.61 ± 0.43	1.71 ± 0.45	0.10 ± 0.10***	0.26	*PLA vs CON:*			
Control (CON)	1.54 ± 0.29	1.54 ± 0.22	0.01 ± 0.10	0.02	0.09 ± 0.08	0.24	5.10	0.03*
10m sprint (s)								
Placebo (PLA)	1.61 ± 0.10	1.60 ± 0.11	− 0.01 ± 0.03	− 0.06	*PLA vs CON:*			
Control (CON)	1.63 ± 0.12	1.62 ± 0.12	− 0.01 ± 0.03	− 0.11	0.01 ± 0.02	0.05	0.24	0.67
20m sprint (s)								
Placebo (PLA)	2.92 ± 0.19	2.90 ± 0.19	− 0.03 ± 0.06	− 0.13	*PLA vs CON:*			
Control (CON)	2.95 ± 0.21	2.94 ± 0.19	− 0.01 ± 0.06	− 0.07	− 0.01 ± 0.04	− 0.06	0.52	0.50
CMJ Jump height (cm)								
Placebo (PLA)	38.2 ± 7.21	38.6 ± 7.2	0.4 ± 1.8	0.07	*PLA vs CON:*			
Control (CON)	34.1 ± 5.01	34.8 ± 5.5	0.7 ± 2.1	0.12	− 0.26 ± 1.54	− 0.04	0.27	0.80
Leg press power (w/bw)								
Placebo (PLA)	20.2 ± 3.3	20.0 ± 3.4	− 0.2 ± 1.3	− 0.07	*PLA vs CON:*			
Control (CON)	19.2 ± 2.8	18.9 ± 2.7	− 0.3 ± 1.1	− 0.09	0.06 ± 0.83	0.02	0.36	0.74
Muscle thickness (mm)								
Placebo (PLA)	23 ± 4.7	24.0 ± 5.4	1.0 ± 1.3#	0.24	*PLA vs CON:*			
Control (CON)	24 ± 3.8	24.2 ± 4.1	0.2 ± 2.0	0.05	0.78 ± 2.12	0.20	0.89	0.27

Table 2. Results from the main groups, individualized (Placebo [PLA]) vs control group (Control [CON]). *1RM* 1-repetition maximum, *CMJ* countermovement jump, *kg* kilogram, *s* seconds, *cm* centimeters, *W* Watts, *mm* millimeters. ***p < 0.001, **p < 0.01, *p < 0.05.

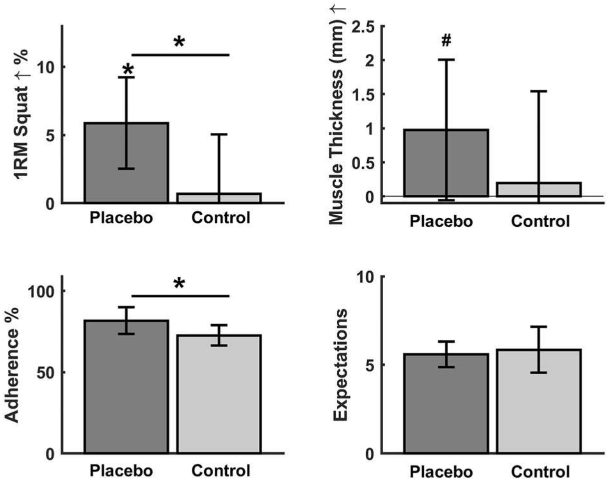

Figure 2. Illustrating percent change in 1RM (*One repetition maximum*) squat, change in muscle thickness (mm: millimeters), Adherence between groups measured as percentage of completed scheduled training sessions as well as median expectation (SETS: Stanford Expectations of Treatment Scale) of the placebo and control group. $^{*}p < 0.05$ $^{\#}p < 0.10$, where the horizontal line represent group changes. Error bars represent 95% confidence intervals (except for SETS which illustrate median with upper and lower quartiles).

distributed in Control, and the subjects in the lower quartile of Control had lower expectations towards the training intervention compared to Placebo ($r = 0.72$ [rank-biserial coefficient of correlation], BF_{10}: 2.1, $p = 0.033$, Fig. 3). Additionally, there was a strong correlation between changes in muscle thickness and changes in 1RM squat ($r = 0.58$, BF_{10}: 6.3, $p = 0.025$). There was no correlation between adherence and changes in 1RM squat ($r = -0.12$, BF_{10}: 0.2, $p = 0.53$). There were no changes in bodyweight in any of the groups (Placebo: -0.2 ± 1.7 kg, $p = 0.66$, Control: 0.0 ± 0.9 kg, $p = 0.96$).

No significant differences were observed in any of the performance measures when comparing all participants doing the actual theoretical "optimal" individualized training vs participants performing generic power training. Notably, all participants in the «Individualized» training subgroups were deemed “velocity oriented” by the calculations from Samozino et al.[12], and conducted high-load strength training.

Discussion

The study’s key finding was that, despite undergoing the same training, participants who were told they were in the intervention group (Placebo) improved their 1RM squat more than those in the control group (Control). Additionally, the subjects in the placebo group tended to increased muscle thickness, which was strongly correlated with changes in leg strength.

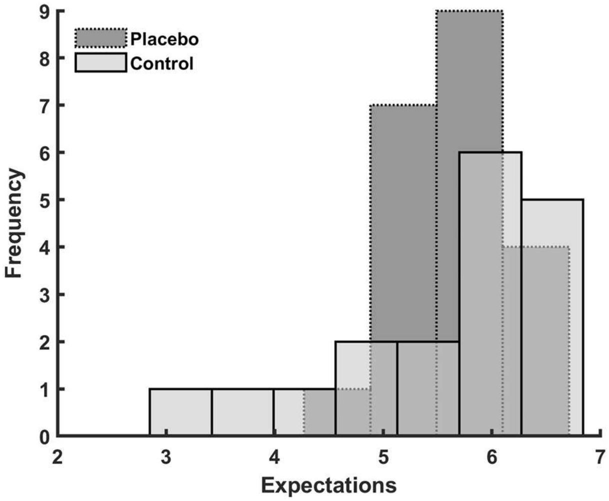

Figure 3. Frequency distribution of the expectations for the placebo vs control group.

To the author's knowledge, this is the first study investigating the placebo effect as a consequence of altering participants' expectations of a training intervention. A recent review on the topic summarized the findings of placebo research in sports science and found a pooled effect size of 0.37, combining a variety of placebo treatments[6]. Further, the effects varied depending on the type of Placebo administered[6]. Nutritional and mechanical ergogenic aids both had small to moderate placebo effects (ES: 0.35–0.47)[6,27,28]. The effects of anabolic steroids as a placebo had the greatest impact on performance (ES: 1.44)[6,29,30]. The effects of a placebo evoked by an erythropoietin-like (EPO) drug on performance were likewise found to elicit large effects (ES: 0.81)[31]. The placebo effect of Transcutaneous Nerve Stimulation (TENS) was observed to have moderate to high effect sizes (ES: 0.70–1.02)[6,32,33], whereas amino acids, caffeine, and placebo tennis rackets have small to moderate effect sizes (ES: 0.36–0.40)[6,34–36]. Fake sports supplements were shown to have small effects on performance (ES: 0.21)[37]. Coldwater immersion, sodium bicarbonate, ischemia preconditioning, carbohydrate, -alanine, kinesiology tape, and magnetic wristbands had no measurable effect[6,38–40]. The effect size in the present study (ES: 0.26) is comparable to the literature, where the fake sports supplements might be the studies with the most comparable effects and study designs. Specifically, the subjects are tested in physical performance measures, whereas some are told they get a performance-enhancing substance, and others get the same substance, but are told it does not increase performance. Notably, the main difference in our present study is the training duration, as most other placebo studies investigate acute measures[6]. Additionally, our emphasis was on the training configurations of the training program and not from a nutritional substance. Previous studies usually see larger strength gains in 10-week training periods ($ES > 0.50$), however as the present study were in season for the athletes, smaller effects would be expected[41,42].

Placebo (and nocebo) effects encompass a broad range of events that aren't confined to a direct response to a placebo (or nocebo) treatment[2]. In both a placebo and treatment condition, all the parameters associated with the delivery/engagement of the intervention are included in the results[6]. Expectations, prior experiences, the participant-researcher relationship, trust, empathy, and the ritual surrounding administration are just a few examples[2,5,6]. Those who have attempted to quantify maximal athletic performances, for example, are aware that not all "max" attempts are truly maximal and representational of capacity. As scientists, we usually say things like "subjects were verbally motivated and encouraged to provide their best effort," but what does that really mean? Are we aware of the subjects' pre-conceived thoughts and expectations? Consequently, it is possible that subjects in the placebo group have higher expectations of themselves (or think the researchers expect more of them), and therefore push their limits just slightly more than the subjects that believe they are in the control group[2,5,6]. Such a notion cohere with the results of the present study, as only the 1RM squat showed a significant group difference, where the weight is increased based on participants' and researchers' judgment. Oppositely, the jumping, sprinting, and power tests are slightly less influenced by subjective judgment. Interestingly, although subjective expectations during testing might influence the results, only the placebo group increased muscle thickness, which was not true for the control group. Indicating that there might be part of the placebo effect independent of the testing context. Notably, one should also keep in mind the small sample size and relatively small increase in muscle thickness compared to the measurement error. Another possible explanation for the differences observed is the dissimilarities in expectations towards the intervention, which again predicted the adherence to the training program (Fig. 4). The measure for expectations were non-normal distributed, where it was only a clear difference in expectation for the lower percentile (Fig. 3). The low number of participants and the less sensitive nature of such a questionnaire measure, could be the reason for not observing any stronger difference between groups.

The adherence to the training program appears at first to be an obvious explanation of the group difference in strength gains; however, such a notion is not evident. First, the adherence was not associated with the strength gains ($r = -0.12$) nor a significant moderator in an ANCOVA analysis. Therefore, the larger increase in strength

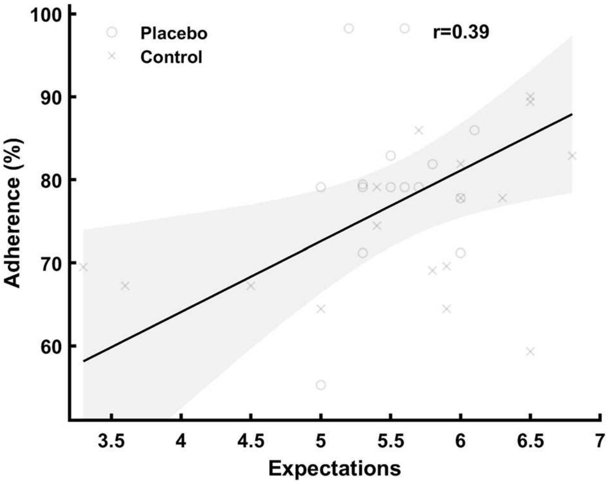

Figure 4. Correlation between the adherence to the training program and expectations toward the training intervention. Adherence is measured as percentage of completed scheduled training sessions and expectation using SETS (Stanford Expectations of Treatment Scale).

in the placebo group seems to be independent of the adherence. Such observation is not surprising, as more training is not always better, especially considering the athletes in the present study were in their competitive season with frequent practice and matches[43]. Secondly, another plausible explanation for the strength gain is higher "quality" training in the placebo group vs. the control group[44]. It is, for example, well documented that the intention to move weights with maximal intentional effort has an impact on training adaptations[44]. Further, it is shown that varying motivational strategies during resistance training influence the exercise performance (i.e., effort/velocity of the movements)[45]. For example, a higher effort is induced by giving athletes feedback during training[45], creating inter-subject competitiveness[46], and giving verbal encouragement[47] among other strategies[48]. It is possible that the subjects in the placebo group performed the training with higher "quality" (i.e., effort) than the subjects in the placebo group, which further influenced the training results. On a similar note, there is also a possibility that the participants in the placebo group might have modified other habits such as sleep or nutrition, or even performed extra exercises outside their allocated program. Unfortunately, due to practical limitations and covid restrictions, we could not supervise and oversee the training sessions or lifestyle habits which could have confirmed or rejected these speculations.

There were no significant differences in any of the included measures regarding the effectiveness of the "individualized training", independent of the placebo group allocation (Table 3). To the authors' knowledge, eight experimental studies have evaluated the effectiveness of individualized training based on force–velocity profiling[13–20]. Four studies did not find any effects in favor of individualized training based on the FV-profile[17–20]. Furthermore, of the four remaining studies, only two included a control group performing a "non-optimized" training regimen for comparison[15,16]. The creators of the concept performed the first of the two studies, where they found large effect sizes from the intervention (ES: 0.7–1.0), with no change in the control group (ES: 0.14)[15,16]. In the latter study by Simpson et al.[15,16] slightly lower effects were found with effect sizes of 0.37 vs 0.12 for the intervention vs control group, respectively. Notably, according to the original calculations underlying the entire concept of training according to the FV profile, the results from both studies are ~ 5–7 larger than the theoretical framework can account for (Supplement 1). Meaning, that even if one were to accept the hypothesis of individualizing training according to the FV profile, the previous results cannot be explained by the theory alone. Because researchers' and participants' expectations of the intervention can significantly impact the study's outcome, both studies' results are probably confounded by placebo effects[9–11].

The present study included a large group of trained athletes from handball and soccer, both male and females. Although the experiment was performed as a multicenter study, the same test leaders and equipment were used at all the locations at both testing time points. All the participants were classified as velocity-dominated or well-balanced, resulting in an uneven distribution of participants across the range of FV profiles. As a result, it is impossible to compare smaller subgroups, such as different training regimens for different deficiencies. Importantly, as such uneven allocation is reported in earlier research, the current study was designed with that in mind, where the main analysis is independent of the sub-groups (i.e., both Placebo and Control are on average doing the same type of training). Additionally, the various programs in the subgroups have different training modalities and total volumes calculated as sets × reps, which may influence the sub-group outcomes. The effects

	Pre	Post	Change		Group difference			
Variable and group	**Mean ± SD**	**Mean ± SD**	**Δ ± SD**	**ES**	**Mean ± 95% CI**	**ES**	**BF_{10}**	**p-value**
1RM squat (kg/bw)								
Strength and power (BAL)	1.61 ± 0.36	1.64 ± 0.31	0.03 ± 0.11	0.09	*BAL vs STR:*			
High load strength (STR)	1.55 ± 0.41	1.64 ± 0.46	0.09 ± 0.10**	0.25	− 0.06 ± 0.08	− 0.16	0.70	0.15
10m sprint (s)								
Strength and power	1.61 ± 0.11	1.60 ± 0.11	− 0.01 ± 0.03	− 0.05	*BAL vs STR:*			
High load strength	1.63 ± 0.11	1.62 ± 0.11	− 0.01 ± 0.03	− 0.12	0.01 ± 0.02	0.06	0.40	0.55
20m sprint (s)								
Strength and power	2.91 ± 0.20	2.89 ± 0.20	− 0.02 ± 0.05	− 0.09	*BAL vs STR:*			
High load strength	2.96 ± 0.20	2.94 ± 0.19	− 0.02 ± 0.07	− 0.11	0 ± 0.04	0.02	0.34	0.88
CMJ Jump height (cm)								
Strength and power	36.6 ± 5.51	37.4 ± 5.8	0.9 ± 1.8#	0.14	*BAL vs STR:*			
High load strength	35.4 ± 7.31	35.7 ± 7.3	0.3 ± 2.1	0.04	0.6 ± 1.54	0.10	0.45	0.39
Leg press power (w/bw)								
Strength and power	20.5 ± 2.7	20.2 ± 2.7	− 0.3 ± 1.3	− 0.12	*BAL vs STR:*			
High load strength	18.7 ± 3.2	18.6 ± 3.3	− 0.1 ± 1.1	− 0.04	− 0.25 ± 0.83	− 0.09	0.37	0.55
Muscle thickness (mm)								
Strength and power	23.5 ± 3.8	23.8 ± 4.2	0.3 ± 2.1	0.08	*BAL vs STR:*			
High load strength	23.6 ± 4.6	24.3 ± 5.1	0.7 ± 1.5	0.18	− 0.4 ± 2.12	− 0.10	0.44	0.63

Table 3. Results from the sub-groups, strength and power training (BAL) vs high load strength program (STR). *1RM* 1-repetition maximum, *CMJ* countermovement jump, *kg* kilogram, *s* seconds, *cm* centimeters, *W* Watts, *mm* millimeters. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

we found in the present study were small and would most likely be more prominent if a greater emphasis were placed on inducing a "nocebo" effect in the control group. Nevertheless, as the athletes were in their competitive season, such focus was not regarded as ethical, and it's probably hard to include high-level athletes in such an experiment. Due to the relatively small sample size, the present study should be considered a pilot study, where future full powered trials should be conducted. When interpreting the results from the ultrasound measurements, it is important to consider both the sample size, as well as the observed increases in relation to the measurement error. The small sample size, in combination with a modest increase in muscle thickness, increase the likelihood of random error, making it more difficult to draw definitive conclusions from the data. Similarly, it is worth noting that there was no significant differences between groups in the CMJ, Sprint and leg press measurements. Consequently, there is always a possibility that positive findings in the present study are coincidental and should rather be interpreted together with the broader literature, and not in isolation.

Another limitation in the present study is the lack of tight control of the training sessions performed by the participants. On the other hand, this can also be considered to increase the ecological validity and applicability, as a large portion of training studies are indeed performed under less controlled situations. Finally, we postulated probable mediators of the placebo effect, which should be investigated further in future research to understand the topic better.

Conclusion

To the author's knowledge, this is the first study to investigate the placebo effect of believing to receive optimal training vs. a generic training program. The results suggest that the placebo effect may explain meaningful outcome variances in sports and exercise training interventions. Future research is needed to better understand the mediators and moderators of the placebo impact on adaptations to training and improvements in sport performance.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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References

1. Younger, J. *et al.* Development of the Stanford Expectations of Treatment Scale (SETS): A tool for measuring patient outcome expectancy in clinical trials. *Clin. Trials* **9**(6), 767–776 (2012).
2. Beedie, C. J. & Foad, A. J. The placebo effect in sports performance. *Sports Med.* **39**(4), 313–329 (2009).
3. McQuay, H. & Moore, R. A. Placebo. *Postgrad. Med. J.* **81**(953), 155–160 (2005).
4. Patulin Clinical Trials Committee, Medical Research Council. Clinical trial of patulin in the common cold. *Int. J. Epidemiol.* **2**, 373–374 (1944).
5. Beedie, C. *et al.* Consensus statement on placebo effects in sports and exercise: The need for conceptual clarity, methodological rigour, and the elucidation of neurobiological mechanisms. *Eur. J. Sport Sci.* **18**(10), 1383–1389 (2018).
6. Hurst, P. *et al.* The Placebo and Nocebo effect on sports performance: A systematic review. *Eur. J. Sport Sci.* **20**(3), 279–292 (2020).
7. Gu, A. P. *et al.* Sham surgical procedures for pain intervention result in significant improvements in pain: Systematic review and meta-analysis. *J. Clin. Epidemiol.* **83**, 18–23 (2017).
8. Kaptchuk, T. J. *et al.* Do medical devices have enhanced placebo effects? *J. Clin. Epidemiol.* **53**(8), 786–792 (2000).
9. Brown, W. A. Expectation, the placebo effect and the response to treatment. *R I Med. J.* **98**(5), 19 (2015).
10. Halson, S. L. & Martin, D. T. Lying to win—placebos and sport science. *Int. J. Sports Physiol. Perform.* **8**(6), 597–599 (2013).
11. Holman, L. *et al.* Evidence of experimental bias in the life sciences: Why we need blind data recording. *PLoS Biol.* **13**(7), e1002190 (2015).
12. Samozino, P. *et al.* Optimal force–velocity profile in ballistic movements—Altius: Citius or fortius. *Med. Sci. Sports Exerc.* **44**(2), 313–322 (2012).
13. Jiménez-Reyes, P. *et al.* Effectiveness of an individualized training based on force-velocity profiling during jumping. *Front. Physiol.* **7**, 677 (2017).
14. Álvarez, J. A. E. *et al.* Individualized training based on force-velocity profiling during jumping in ballet dancers. *Int. J. Sports Physiol. Perform.* **1**(aop), 1–7 (2019).
15. Jiménez-Reyes, P., Samozino, P. & Morin, J.-B. Optimized training for jumping performance using the force-velocity imbalance: Individual adaptation kinetics. *PLoS One* **14**(5), e0216681 (2019).
16. Simpson, A. *et al.* Optimised force-velocity training during pre-season enhances physical performance in professional rugby league players. *J. Sports Sci.* **39**, 91–100 (2021).
17. Lindberg, K. *et al.* Should we individualize training based on force-velocity profiling to improve physical performance in athletes?. *Scand. J. Med. Sci. Sports* **31**, 2198–2210 (2021).
18. Rakovic, E. *et al.* The effect of individualised sprint training in elite female team sport athletes: A pilot study. *J. Sports Sci.* **36**(24), 2802–2808 (2018).
19. Zabaloy, S. *et al.* Effects of individualized training programs based on the force-velocity imbalance on physical performance in rugby players, pp. 1–10 (2020) **(preprint)**.
20. Lindberg, K. *et al.* The effectiveness of Individualized training based on force-velocity profiling on physical function in older men. *Scand J. Med. Sci. Sports* **32**, 1013–1023 (2022).
21. Lindberg, K. *et al.* Force-velocity profiling in athletes: Reliability and agreement across methods. *PLoS One* **16**(2), e0245791 (2021).
22. Lindberg, K. *et al.* Strength and power testing of athletes: A multicenter study of test–retest reliability. *Int. J. Sports Physiol. Perform.* **17**, 1103–1110 (2022).
23. Lindberg, K. *et al.* Strength and power testing of athletes: Associations of common assessments over time. *Int. J. Sports Physiol. Perform.* **17**(8), 1280–1288 (2022).
24. Skorski, S. & Hecksteden, A. Coping with the «small sample-small relevant effects» dilemma in elite sport research. *Int. J. Sports Physiol. Perform.* **16**, 1559–1560 (2021).
25. Hecksteden, A., Kellner, R. & Donath, L. Dealing with small samples in football research. *Sci. Med. Footb.* **6**, 389–397 (2022).
26. Jeffreys, H. *The Theory of Probability* (OUP, 1998).

27. Beedie, C. J. *et al.* Positive and negative placebo effects resulting from the deceptive administration of an ergogenic aid. *Int. J. Sport Nutr. Exerc. Metab.* **17**(3), 259–269 (2007).
28. Pires, F. O. *et al.* Caffeine and placebo improved maximal exercise performance despite unchanged motor cortex activation and greater prefrontal cortex deoxygenation. *Front. Physiol.* **9**, 1144 (2018).
29. Ariel, G. & Saville, W. Effect of anabolic steroids on reflex components. *J. Appl. Physiol.* **32**(6), 795–797 (1972).
30. Maganaris, C. N., Collins, D. & Sharp, M. Expectancy effects and strength training: Do steroids make a difference?. *Sport Psychol.* **14**(3), 272–278 (2000).
31. Ross, A. *et al.* The relationship between physical characteristics and match performance in rugby sevens. *Eur. J. Sport Sci.* **15**(6), 565–571 (2015).
32. Pollo, A. *et al.* Preventing motor training through nocebo suggestions. *Eur. J. Appl. Physiol.* **112**(11), 3893–3903 (2012).
33. Fiorio, M. *et al.* Placebo-induced changes in excitatory and inhibitory corticospinal circuits during motor performance. *J. Neurosci.* **34**(11), 3993–4005 (2014).
34. Kalasountas, V., Reed, J. & Fitzpatrick, J. The effect of placebo-induced changes in expectancies on maximal force production in college students. *J. Appl. Sport Psychol.* **19**(1), 116–124 (2007).
35. Saunders, B. *et al.* Placebo in sports nutrition: A proof-of-principle study involving caffeine supplementation. *Scand. J. Med. Sci. Sports* **27**(11), 1240–1247 (2017).
36. Guillot, A. *et al.* Motor imagery and 'placebo-racket effects' in tennis serve performance. *Psychol. Sport Exerc.* **13**(5), 533–540 (2012).
37. Hurst, P. *et al.* Athletes intending to use sports supplements are more likely to respond to a placebo. *Med. Sci. Sports Exerc.* **49**, 1877–1883 (2017).
38. Broatch, J. R., Petersen, A. & Bishop, D. J. Postexercise cold water immersion benefits are not greater than the placebo effect. *Med. Sci. Sports Exerc.* **46**(11), 2139–2147 (2014).
39. Bellinger, P. M. & Minahan, C. L. Performance effects of acute β-alanine induced paresthesia in competitive cyclists. *Eur. J. Sport Sci.* **16**(1), 88–95 (2016).
40. Poon, K. Y. *et al.* Kinesiology tape does not facilitate muscle performance: A deceptive controlled trial. *Man. Ther.* **20**(1), 130–133 (2015).
41. Freitas, T. T. *et al.* Short-term adaptations following complex training in team-sports: A meta-analysis. *PLoS One* **12**(6), e0180223 (2017).
42. Bauer, P. *et al.* Combining higher-load and lower-load resistance training exercises: A systematic review and meta-analysis of findings from complex training studies. *J. Sci. Med. Sport* **22**(7), 838–851 (2019).
43. Figueiredo, V. C., de Salles, B. F. & Trajano, G. S. Volume for muscle hypertrophy and health outcomes: The most effective variable in resistance training. *Sports Med.* **48**(3), 499–505 (2018).
44. González-Badillo, J. J. *et al.* Maximal intended velocity training induces greater gains in bench press performance than deliberately slower half-velocity training. *Eur. J. Sport Sci.* **14**(8), 772–781 (2014).
45. Jiménez-Alonso, A. *et al.* Effect of augmented feedback on velocity performance during strength-oriented and power-oriented resistance training sessions (2020).
46. Campenella, B. *et al.* Effect of visual feedback and verbal encouragement on concentric quadriceps and hamstrings peak torque of males and females. *Isokinet. Exerc. Sci.* **8**(1), 1–6 (2000).
47. McNair, P. J. *et al.* Verbal encouragement: Effects on maximum effort voluntary muscle action. *Br. J. Sports Med.* **30**(3), 243–245 (1996).
48. Nickerson, B. S. *et al.* Evaluation of load-velocity relationships and repetitions-to-failure equations in the presence of male and female spotters. *J. Strength Cond. Res.* **34**(9), 2427–2433 (2020).

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Author contributions

Contributions to the conception or design of the study: K.L., T.B., G.P., P.S.; Performed experiments: K.L., F.T.V., M.J., M.K., O.S., H.S.G., G.S.F., R.B.; Analyzed data: K.L., M.J.; Interpreted results of research: K.L., T.B., G.P., P.S.; Drafted manuscript and prepared tables/figures: K.L.; Edited, critically revised paper: K.L., T.B., F.T.V., G.P., M.J., M.K., O.S., H.S.G., G.S.F., R.B., P.S.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to K.L.

Appendix I

Forespørsel om deltakelse i forskningsprosjektet

Testing av styrke, hastighet og power

I regi av Olympiatoppen

Bakgrunn og hensikt

Dette er en forespørsel til deg som er idrettsutøver (minimum nasjonalt nivå). Du må være mellom 18 og 40 år og du kan ikke delta om du har skader i muskelskjelettapparatet som hindrer deg i å yte maksimalt i styrke-, spenst- og sprinttester. Du kan heller ikke delta om du tar reseptbelagte medisiner som kan påvirke din fysiske prestasjonsevne.

Studien har til hensikt å undersøke nøyaktigheten og sammenhengen mellom ulike styrke-, spenst- og sprinttester. Prestasjonsnivået i spenst- og sprinttester avhenger av både kraft og hastighet i bevegelsene (kraft [N] x hastighet [m/s] = effekt [W]). Ved å måle hva som er mest begrensende – kraft eller hastighet – kan vi si noe om dine grunnleggende egenskaper og hva du bør prioritere i treningsarbeidet. Ulike tester har fordeler/styrker og ulemper/svakheter og i dette prosjektet ønsker vi se om egenskapene kraft og hastighet kommer til uttrykk på samme måte når de testes på ulike måter med forskjellig utstyr.

Hva innebærer studien?

Studien innebærer at du som forsøkspersonen gjennomfører en serie av styrke-, spents- og sprinttester på fire ulike dager. Tesingen vil ta 2-3 timer per dag. De to første testdagene gjennomføres med ca én ukes mellomrom. Deretter følger 2-6 mnd før de to siste testdagene gjennomføres med ca én ukes mellomrom. Testene inkluderer alle eller et utvalg av disse testene:

1. Spensthopp på kraftplattform
2. Hopping med vekter (stang på nakken)
3. Knebøy med økende motstand til maks.
4. Beinpress (lufttrykkmotstand) med økende motstand til maks.
5. 40 m sprint
6. Sykkelsprint (6 sek.)

Du skal også gjennomføre en DXA-skann tidlig på morgenen (før frokost) på en av testdagene eller en annen dag i forbindelse med de to første testdagene.

I to dager før hver testdag må du trene lett, eller hvile. Lett trening vil si trening du antar ikke vil svekke styrken, spensten eller hurtigheten din. Hvis du trener, er det viktig at du gjør den samme treningen før hver testdagene (standardiser treningen).

Mulige fordeler og ulemper

Fordeler:

- Som forsøksperson vil du få målt styrke-, spenst- og sprintegenskaper. Du vil således ha muligheten for å tilegne deg mer kunnskap om din kapasitet og dine begrensninger.

Ulemper:

- Tid må avsettes til gjennomføring av trening og testing.
- Trening og testing kan føre til stølhet og oppfattes som ubehagelig/smertefullt i etterkant.

- Det er en risiko for skader ved både testing og trening, men ikke større enn ved trening du er vant med fra før.
- Målingen av kroppssammensetningen gjøres med DXA (Dual energy X-ray Absorptiometry). Metoden medfører en røntgenstrålingsdose. Dosen anses som lav og kan sammenliknes med strålingsdosen man utsettes for under en interkontinental flyreise.

Hva skjer med informasjonen om deg?
Alle testresultater vil bli behandlet uten navn og fødselsnummer eller andre direkte persongjenkjennende opplysninger. En kode knytter deg til dine opplysninger og testresultater gjennom en navneliste. Det er kun prosjektleder som har adgang til navnelisten og som kan finne tilbake til deg. Listen destrueres så snart studien er gjennomført. Det vil ikke være mulig å identifisere deg i resultatene av studien når disse publiseres.

Frivillig deltakelse
Det er frivillig å delta i studien. Dersom du ønsker å delta, undertegner du samtykkeerklæringen på siste side. Om du nå sier «ja» til å delta, kan du senere, når som helst og uten å oppgi grunn, trekke tilbake ditt samtykke. Dette vil ikke medføre noen konsekvenser for deg. Dersom du senere ønsker å trekke deg eller har spørsmål til studien, kan du kontakte:

Gøran Paulsen, PhD, Fagansvarlig for kraft/styrke i Olympiatoppen (Norges idrettsforbund) tlf.: +4793429420; epost: goran.paulsen@olympiatoppen.no

Ytterligere informasjon om studien finnes i kapittel *A – utdypende forklaring av hva studien innebærer.*
Ytterligere informasjon om biobank, personvern og forsikring finnes i kapittel B – *Personvern, biobank, økonomi og forsikring.*

Samtykkeerklæring følger etter kapittel B.

Kapittel A- utdypende forklaring av hva studien innebærer

- Kriterier for deltakelse
    - Alder: 18-40 år
    - Kjønn: Mann eller kvinne
    - Ikke røyker
    - Trener regelmessig, og er utøver på minimum nasjonalt nivå (topp 100)
    - Ingen betydningsfulle sykdommer eller medisinbruk

- Tester og utstyr:
  Spenst på kraftplattform (Musclelab®, Ergotest, Langesund, Norge): 1) Svikthopp og knebøyhopp, 2) svikthopp/knebøyhopp med 5 motstander fra 10-120 kg (individuell fordeling av motstander).
  Knebøy (encoder; Musclelab®, Ergotest, Langesund, Norge): 5 motstander fra 50-200 kg (individuell fordeling av motstander).
  Beinpress (Keiser®, Air300, A420, Fresno, CA, USA): Sittende beinpress med 10 motstander.
  Sprintløp med fotoceller (Musclelab®, Ergotest, Langesund, Norge): 40 m sprint (målinger hver 5 m).
  Sykkelsprint (Wattbike Ltd, Nottingham, UK): 6 sekunder varighet.
  Kroppssammensetningsmåling (Lunar iDXA, General Electric Company, Madison).

- Mulige fordeler
  Se ovenfor
- Mulige bivirkninger
  Se ovenfor
- Mulige ubehag/ulemper
  Se ovenfor
- Pasientens/studiedeltakerens ansvar
  Forsøkspersonens ansvar består i å:
    - Komme til avtalte tider og følge retningslinjer for forberedelser til testing.
    - Følge treningsprogrammet og registrere treningen i en dagbok.

Kapittel B - Personvern, biobank, økonomi og forsikring

Personvern
Opplysninger som registreres om deg er:

- Alder
- Kjønn
- Høyde
- Vekt
- Styrke, spenst og hurtighet
- Trening utover det som gjøres i prosjektet (treningsdagbok)

Høgskolen i Innlandet (Lillehammer) er ansvarlig for all informasjon som samles inn i dette prosjektet. Informasjon om deg vil behandles avidentifisert (regneark, databaser, osv.). Det betyr at vi gir deg et forsøkspersonnummer og linker all innsamlet informasjon til dette nummeret. Vi har en kodeliste (ett eksemplar) som kobler navnet ditt til forsøkspersonnummeret. Kodelisten oppbevares i et låsbart skap og det er kun forskningsmedarbeidere i prosjektet som har tilgang (Gøran Paulsen og Bent Ronny Rønnestad). Prosjektet avsluttes 31.12 2022 og da vil kodelisten destrueres, noe som betyr at innsamlet informasjonen er anonymisert og ingen opplysninger kan spores tilbake til deg.

Rett til innsyn og sletting av opplysninger om deg og sletting av prøver
Hvis du sier ja til å delta i studien, har du rett til å få innsyn i hvilke opplysninger som er registrert om deg. Du har videre rett til å få korrigert eventuelle feil i registrerte opplysninger. Dersom du trekker deg fra studien, kan du kreve å få slettet innsamlede opplysninger/data, med mindre opplysningene allerede er inngått i vitenskapelige publikasjoner.

Økonomi
Studien er finansiert gjennom forskningsmidler fra Olympiatoppens FoU-midler (2017).

Forsikring
Utøvere som tests og trener i Olympiatoppens lokaler er forsikret.

Informasjon om utfallet av studien
Forsøkspersoner får utlevert egne resultater og det vil avholdes et informasjonsmøte for forsøkspersonene i etterkant av forsøkene. Resultatene fra alle forsøkspersonene vil bli publisert i et internasjonalt, fagfellevurdert tidsskrift.

Samtykke til deltakelse i studien

Jeg er villig til å delta i studien og bekrefter å ha mottatt og lest informasjon om studien

----
(Signert av prosjektdeltaker, dato)

Jeg bekrefter å ha gitt informasjon om studien

(Signert, rolle i studien, dato)

Appendix II

Forespørsel om deltakelse i forskningsprosjekt

"Optimal trening for kraft og hastighet"

Bakgrunn og hensikt

I idretter som stiller krav til hurtighet og spenst må utøveren kombinere styrketrening med tunge vekter på ene siden, samt sprint- og spenst-trening med kroppsvekt eller lett motstand på den andre. I mellom disse ytterpunktene har vi olympiske løft og «power-trening» med moderat tunge vekter. Det er en utfordring for mange utøvere å finne balansen mellom disse treningsmetodene, og i lagidretter trener ofte alle utøvere likt, selv om det er store individuelle forskjeller i fysiske styrker og svakheter. Nye studier peker i retning av en mer individualisert styrketrening, der den prioriterte metoden bestemmes av spesielle kraft-hastighets-tester. Eksempelvis bør muligens en utøver som har stor styrke, men lav hastighet, prioritere spenst- og hurtighetstrening.

Vi kan imidlertid stille spørsmålstegn ved resonnementet ovenfor, om hvorvidt idrettsutøvere bør fokusere på å forbedre «svakheter». Erfaring fra arbeid med toppidrettsutøvere i Olympiatoppen indikerer at man heller bør fokusere på å videreutvikle deres «styrker», da det er nettopp dette som ofte er årsaken til at de presterer på høyt nivå i sin idrett. Med andre ord, en utøver som har en kraft-hastighets-profil som tilsier stor styrke og lav hastighet bør kanskje prioritere tung styrketrening.

Hva innebærer det for deg å delta i denne studien?

Dette er et spørsmål til deg som er idrettsutøver om å delta i et forskningsprosjekt der hensikten er å undersøke effekten av individualisert trening for kraft og hastighet. Studien blir gjennomført av forskere ved Olympiatoppen i Oslo, Region Sør og Region Øst. Testing og trening vil foregår på de respektive treningssentra og laboratoriene i Kristiansand/Arendal og Fredrikstad.

Studien innebærer at du som deltaker gjennomfører forskjellige tester for styrke, spenst og hurtighet over 2 dager før og 2 dager etter en 10 ukers treningsperiode. Testingen vil ta ca. 3 timer per dag, og det vil være minst 3 dager mellom testdagene. Du skal også ta en DXA-skann for å undersøke kroppssammensetning tidlig på morgenen (før frokost) på en av testdagene eller i løpet av den uken det er testing før og etter trening.

Etter testene blir dine resultater benyttet for å plassere deg i en gruppe som trener med fokus på enten 1) mot å optimalisere kraft-hastighets-forholdet (trener på dine «svakheter»), 2) trener «motsatt» og har som mål å bedre dine «styrker» (enten hastighet eller kraft) eller 3) å bedre begge egenskaper ("balansert gruppe", både kraft og hastighet). Det vil være 2 økter per uke i 10 uker. Du vil bli testet igjen etter 4 uker trening (midtveis) og.

For utdypende informasjon om prøver og testing, se Vedlegg A under.

Mulige ulemper ved å delta i denne studien

Risiko eller ubehagene som kan oppstå i forbindelse med deltakelse anses som minimal, men mulige risikofaktorer er utdypet nedenfor:

- Tid må avsettes til testing og trening og dette KAN gå utover annen trening
- Testing og trening kan føre til stølhet og oppfattes som smertefullt/ubehagelig.
- Det er alltid en risiko for skader ved både trening og testing, men disse anses ikke som større enn den treningen du er vant til fra før.
- DXA (måling av kroppssammensetning) medfører en lav røntgenstrålingsdose, men anses ikke som farlig og tilsvarer dosen en utsettes for under en interkontinental flyreise.
- Blodprøver: Taking av blodprøver ved å sette en nål inn i en overflateåre er en rutinemessig klinisk prosedyre vanligvis benyttet i det medisinske miljø. Du kan oppleve smerte under innføringen av nålen i huden, eller bli svimmel og føle deg svak. Svimmelhet utgjør ingen langvarig fare, og kan lettes opp umiddelbart ved å sette hodet ned mellom knærne, eller ligge ned. I tillegg kan blåmerker oppstå der blodprøven er tatt, men dette er mer sjenerende enn risikofylt. Det er også en liten risiko for å ha en koagulasjonsform i blodet godt etter å ha tatt blodprøven på grunn av skade på venen eller infeksjon. Disse komplikasjonene er svært sjeldne. Bruk av steril teknikk, inkludert sterile blodoppsamlingsapparater, og overholdelse av standard medisinske forholdsregler reduserer enhver risiko til et minimum. En trent prøvetaker vil utføre alle blodprøver.

Fordeler ved å delta i denne studien
Ved å delta i studien vil du få informasjon som kan være til nytte for din trening:

- Du vil få målt dine styrke- og poweregenskaper
- Du vil få informasjon om din kroppssammensetning
- Du vil få mer informasjon om hvordan spesifikk trening virker på deg

Informasjonen kan hjelpe deg i forbindelse med å optimalisere fremtidige trening. Etter at alle data er gjennomgått vil du motta en personlig skriftlig tilbakemelding på alt som vi har målt på deg under intervensjonen. Din deltakelse bidrar til informasjon for fremtidige idrettsutøvere.

Hva skjer hvis du blir skadet fordi du deltok i denne studien?
Hvis du blir skadet eller blir syk på grunn av deltakelse i denne studien, kontakt Paul Solberg (Telefon: +47 99094092) eller Thomas Bjørnsen (Telefon: +47 98619299) umiddelbart. Medisinsk behandling vil være tilgjengelig via våre avtaler.

Hvilken informasjon vil bli samlet inn og hva skjer med personopplysninger om deg?
Hvis du velger å delta i denne studien, vil forskerne få følgende informasjon om deg, inkludert informasjon som kan identifisere deg: idrettsgren, nivå, alder, høyde, vekt, kroppssammensetning, spenst, styrke, samt informasjon som er relatert til muskelvekst, tilpasning til trening. Samlet vil denne informasjonen benyttes av forskerne til å undersøke effekten av spesifikk trening på idrettsrelaterte egenskaper.

Vi behandler opplysninger om deg konfidensielt og i samsvar med personvernregelverket basert på ditt samtykke. På oppdrag fra Universitetet i Agder har NSD – Norsk senter for forskningsdata AS vurdert at behandlingen av personopplysninger i dette prosjektet er i samsvar med personvernregelverket.

Alle testresultater vil bli behandlet uten navn og fødselsnummer eller andre direkte persongjenkjennende opplysninger. En kode knytter deg til dine opplysninger og resultater gjennom en navneliste so lagres innelåst og som kun databehandlingsansvarlig (Sveinung Berntsen) har tilgang til. Listen destrueres ved prosjektslutt i oktober 2023, du vil da ikke lenger kunne identifiseres. Universitetet i Agder er behandlingsansvarlig institusjon.

Ved å signere denne samtykkeformen bekrefter du at du har lest informasjonen i dette samtykket, fått anledning til å stille spørsmål om denne studien og gir du tillatelse til å bruke resultatene til de formål som er beskrevet.

Frivillig deltakelse og dine rettigheter
Det er frivillig å delta i studien. Du kan når som helst og uten å oppgi noen grunn trekke ditt samtykke til å delta i studien uten at det har noen konsekvenser for deg.

Så lenge du kan identifiseres i datamaterialet, har du rett til:
- innsyn i hvilke personopplysninger som er registrert om deg,
- å få rettet personopplysninger om deg,
- få slettet personopplysninger om deg,
- få utlevert en kopi av dine personopplysninger (dataportabilitet), og
- å sende klage til personvernombudet eller Datatilsynet om behandlingen av dine personopplysninger.

Hvis du har spørsmål til studien, eller ønsker å benytte deg av dine rettigheter, ta kontakt med:
- Thomas Bjørnsen, fagansvarlig kraft/styrke ved Olympiatoppen Sør og stipendiat ved Universitetet i Agder (Telefon: +47 98619299, mail: thomas.bjornsen@uia.no).
- Paul Solberg, faglig leder Olympiatoppen Øst (paul.solberg@olympiatoppen.no, tlf: 99094092).
- Gøran Paulsen, prosjektleder og fagansvarlig for kraft/styrke ved Olympiatoppen Oslo (goran.paulsen@olympiatoppen.no).
- Sveinung Berntsen, databehandlingsansvarlig og professor ved Universitetet i Agder (Telefon: +47 98619299, mail: sveinung.berntsen@uia.no).
- Vårt personvernombud: NSD – Norsk senter for forskningsdata AS, på epost (personverntjenester@nsd.no) eller telefon: 55 58 21 17.

Informasjon om utfallet av studien
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 et internasjonalt tidsskrift.

Biobank
Blodprøver sendes til analyser eller analyser omgående og det skal ikke være behov for oppbevaring av biologisk materiale.

Økonomi
Studien er finansiert gjennom forskningsmidler fra Olympiatoppens FoU-midler (2018-2019). Det er ingen interessekonflikter forbundet med studien.

Forsikring
Alle som testes og trener i Olympiatoppens lokaler er forsikret.

Ytterligere informasjon om studien finnes i kapittel *A – utdypende forklaring av hva studien innebærer.*

Samtykkeerklæring følger etter kapittel A

Kapittel A- utdypende forklaring av hva studien innebærer

Kriterier for deltakelse

- Alder 18-35 år
- Utøver på minimum nasjonalt nivå
- Trener styrke regelmessig
- Ingen betydningsfulle skader, sykdommer eller medisinbruk
- Ikke røyker

Tester, trening og annet den inkluderte må gjennom

Tester gjennomføres 2 ganger over 2 dager under intervensjonsperioden (Før start og etter). Følgende tester gjennomføres begge gangene:

- Svikthopp og knebøyhopp med 5 motstander fra 10-120kg (individuelt)
- 40 meter sprint
- Beinpress (Keiser): Sittende beinpress med 10 motstander
- Sykkelspurter (tre stk. 6 sekunders og en 30 sekunders sprint-test på sykkelergometer)
- Kneekstensjon med 5 motstander
- Kroppssammensetningsmåling (Lunar iDXA)
- Ultralyd måling av lårmusklenes tverrsnittsareal og pennasjonsvinkel
- Blodprøver
- Spørreskjema for opplevd overskudd og motivasjon

Intervensjonen:
Etter at oppstarts-testene er gjennomført vil dine resultater benyttes til å undersøke om du er styrke-dominert, hastighets-dominert eller midt i mellom. Deretter vil du plasseres i en gruppe som 1) trener spesifikt for å utligne dominansen og dermed øke power (arbeidskapasitet), 2) trener «motsatt» og har som mål å bedre sine «styrker» (enten hastighet eller kraft) eller 3) en "balansert gruppe" som trener mot å bedre begge egenskaper (kraft og hastighet).

De 3 gruppene trener 2 økter per uke i totalt 10 uker, der man enten har fokus på styrkeøkter med typiske baseøvelser og styrketrening (1-12 RM), hastighetsfokus som trener sprint- og spenst-trening med kroppsvekt eller lett motstand, eller «power-trening» med moderat tunge vekter.

Tidsskjema – hva skjer og når skjer det?

Testing og trening er planlagt gjennomført høsten 2018 og totalt vil forsøket var 14 uker inkludert testing.

Eventuell kompensasjon til og dekning av utgifter for deltakere

Det er ingen økonomisk kompensasjon i forbindelse med studien.

Deltakers ansvar

- Komme til avtalte tider og følge retningslinjer for forberedelser til trening og testing
- Registrere treningen i en dagbok

Samtykke til deltakelse i studien

Jeg har mottatt og forstått informasjon om prosjektet **”Optimal trening for kraft og hastighet”**, og har fått anledning til å stille spørsmål. Jeg samtykker til:

- ☐ å delta i tester for styrke, spenst og hurtighet over 2 dager før og etter treningsperioden.
- ☐ å delta ta kroppssammensetningsmåling og blodprøver en gang før og etter treningsintervensjon.

Jeg samtykker til at mine opplysninger behandles frem til prosjektet er avsluttet, oktober 2023.

(Signert av prosjektdeltaker, dato)

Jeg bekrefter å ha gitt informasjon om studien

(Signert, rolle i studien, dato)

Appendix III

Vil du delta i forskningsprosjektet

" Effekten av individualisert styrketrening på styrke og eksplosivitet – En randomisert kontrollert studie"

Dette er et spørsmål til deg om å delta i et forskningsprosjekt hvor formålet er å undersøke effekten av individualisert styrketrening basert på kraft-hastighetsprofilering hos trente idrettsutøvere. I dette skrivet gir vi deg informasjon om målene for prosjektet og hva deltakelse vil innebære for deg.

Formål

I idretter som stiller krav til hurtighet og spenst må utøveren kombinere styrketrening med tunge vekter på ene siden, samt sprint- og spenst-trening med kroppsvekt eller lett motstand på den andre. I mellom disse ytterpunktene har vi olympiske løft og «power-trening» med moderat tunge vekter. Det er en utfordring for mange utøvere å finne balansen mellom disse treningsmetodene, og i lagidretter trener ofte alle utøvere likt, selv om det er store individuelle forskjeller i fysiske styrker og svakheter. Nye studier peker i retning av en mer individualisert styrketrening, der den prioriterte metoden bestemmes av spesielle kraft-hastighets-tester. Eksempelvis bør muligens en utøver som har stor styrke, men lav hastighet, prioritere spenst- og hurtighetstrening framfor tung styrketrening. Flere nylige studier støtter denne hypotesen om at individualisering av styrke- og powertrening er viktig for god/optimal utvikling av power i form av spenst og hurtighet. Fra tidligere forskning vet man også at motivasjon til trening påvirker blant annet kvaliteten på gjennomføringen av økten. Det er derfor stor grunn til å tro at mye forskning hvor man sammenligner treningsopplegg, blir påvirket gjennom forventninger og motivasjon man har til treningsopplegget. Formålet med studien er derfor todelt: 1) Undersøke om individualisert trening basert på kraft-hastighets-tester optimaliserer kraft-hastighets-forholdet, og derigjennom forbedrer prestasjon og motivasjon for å trene. 2) Undersøke effekten av forventninger og motivasjon i en styrketreningsintervensjon. Prosjektet vil være med på å gi oss mer kompetanse når det kommer til treningsplanlegging, og være relevant og interessant for både utøvere og de som jobber med idrettsutøvere.

Mulige fordeler og ulemper ved deltakelse i prosjektet

Fordeler:

- Treningsprogrammene er laget for at du skal oppnå økning i maksimal og eksplosiv styrke, samt muskelvekst i trente muskler.
- Du vil få mer informasjon om hvordan spesifikk trening virker på deg
- Som forsøksperson vil du få å tilegne deg mer kunnskap om din kapasitet og prestasjon relatert til styrke, spenst, hurtighet og power, normalt ikke er tilgjengelig for deg.
- Du vil få oppfølging og veiledning før, etter og gjennom powertrening i 8 uker.

Ulemper:

- Tid må avsettes til gjennomføring av trening og testing.
- Trening og testing kan føre til stølhet og oppfattes som ubehagelig/smertefullt i etterkant.
- Det er en risiko for skader ved både testing og trening, men ikke større enn ved trening du er vant med fra før.
- DXA (måling av muskelmasse) medfører en lav røntgenstrålingsdose, men anses ikke som farlig og tilsvarer dosen en utsettes for under en interkontinental flyreise.

Hvem er ansvarlig for forskningsprosjektet?

Universitetet i Agder (UiA) er ansvarlig for prosjektet.

Hvorfor får du spørsmål om å delta?
Du blir spurt om å delta i prosjektet da du treffer målgruppen som er idrettsutøvere på høyt nivå, og du og/eller din fysiske trener har godkjent at vi kan forhøre oss om mulig deltakelse.

Hva innebærer det for deg å delta?
Dette er et spørsmål til deg som er idrettsutøver om å delta i et forskningsprosjekt der hensikten er å undersøke effekten av individualisert trening styrke og eksplosivitet. Studien blir gjennomført av forskere Universitet i Agder, Høgskulen på Vestlandet, og Olympiatoppen i Region Vest og Region Øst. Testing og trening vil foregår på de respektive treningssentra og laboratoriene i Kristiansand, Bergen og Fredrikstad.

Hvis du velger å delta i prosjektet, innebærer det at du

- Gjennomfører 2 treningsøkter per uke i 8 uker
- Gjennomfører fysiske tester fordelt på 2 dager før og etter en 8 ukers treningsperiode
    - Testingen vil ta ca. 2 timer per dag

De fysiske testene består i: Svikthopp med 0,20, 40, 60, og 80 kg, 30m sprint, Beinpress og mål av muskelmasse gjennom Dual x ray absorptiometry (DXA).

Styrketreningen vil bestå av tilsvarende identiske treningsprogram som er brukt i tidligere forskning på individualisert trening basert på kraft-hastighetsprofilering. Dette innebærer 2 økter i uken, over totalt 8 uker, med fokus på styrke og eksplosivitet for bein. Utøveren vil kunne også trene egne økter for overkropp dersom dette er ønskelig.

Det er frivillig å delta
Det er frivillig å delta i prosjektet. Hvis du velger å delta, kan du når som helst trekke samtykket tilbake uten å oppgi noen grunn. Alle dine personopplysninger vil da bli slettet. Det vil ikke ha noen negative konsekvenser for deg hvis du ikke vil delta eller senere velger å trekke deg.

Ditt personvern – hvordan vi oppbevarer og bruker dine opplysninger
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
- Styrke, spenst, hurtighet og muskelmasse

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 forsøkspersonnummer og linker all innsamlet informasjon til dette nummeret. Vi har en kodeliste (ett eksemplar) som kobler navnet ditt til forsøkspersonnummeret. Kodelisten oppbevares i et låsbart skap og det er kun prosjektleder som har tilgang (Thomas Bjørnsen). Prosjektet avsluttes 01.06.2022 og da vil kodelisten destrueres, noe som betyr at innsamlet informasjonen er anonymisert og ingen opplysninger kan spores tilbake til deg.

Hvis du sier ja til å delta i studien, har du rett til å få innsyn i hvilke opplysninger som er registrert om deg. Du har videre rett til å få korrigert eventuelle feil i registrerte opplysninger. Dersom du trekker deg fra studien, kan du kreve å få slettet innsamlede opplysninger/data, med mindre opplysningene allerede er inngått i vitenskapelige publikasjoner. Informasjon som brukes i eventuell vitenskapelig publikasjon vil ikke kunne spores tilbake til deg.

Hva skjer med opplysningene dine når vi avslutter forskningsprosjektet?

Opplysningene anonymiseres når prosjektet avsluttes/oppgaven er godkjent, noe som etter planen er [01.06.2022]. Alle testresultater vil bli behandlet uten navn og fødselsdato eller andre direkte persongjenkjennende opplysninger. En kode knytter deg til dine opplysninger og testresultater gjennom en navneliste. Det er kun prosjektleder som har adgang til navnelisten og som kan finne tilbake til deg. Listen destrueres så snart studien er gjennomført. Det vil ikke være mulig å identifisere deg i resultatene av studien når disse publiseres.

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 rettet personopplysninger om deg,
- å få slettet personopplysninger om deg, og
- å sende klage til Datatilsynet om behandlingen av dine personopplysninger.

Hva gir oss rett til å behandle personopplysninger om deg?

Vi behandler opplysninger om deg basert på ditt samtykke.

På oppdrag fra Universitetet i Agder har NSD – Norsk senter for forskningsdata AS vurdert at behandlingen av personopplysninger i dette prosjektet er i samsvar med personvernregelverket.

Hvor kan jeg finne ut mer?

Hvis du har spørsmål til studien, eller ønsker å benytte deg av dine rettigheter, ta kontakt med:

- Kolbjørn Lindberg, doktorgradsstipendiat ved Universitetet i Agder (kolbjorn.a.lindberg@uia.no, +47 908 70 067)
- Thomas Bjørnsen, prosjektleder og førsteamanuensis ved Universitetet i Agder (thomas.bjornsen@uia.no, +47 986 19 299).
- Paul Solberg, faglig leder Olympiatoppen Øst (paul.solberg@olympiatoppen.no, tlf: 99094092).
- Robert Brankovic, Universitetslektor ved Høgskulen på Vestlandet (r0bertme@gmail.com, +47 977 51 984)
- Morten Kristoffersen, førsteamanuensis ved Høgskulen på Vestlandet (Morten.Kristoffersen@hvl.no, +47 930 92 244)
- Vårt personvernombud: Ina Danielsen (ina.danielsen@uia.no, +47 452 54 401)

Hvis du har spørsmål knyttet til NSD sin vurdering av prosjektet, kan du ta kontakt med:

- NSD – Norsk senter for forskningsdata AS på epost (personverntjenester@nsd.no) eller på telefon: 55 58 21 17.

Med vennlig hilsen

Kolbjørn Lindberg og prosjektmedarbeidere
(stipendiat, forsker og veileder)

Samtykkeerklæring

Jeg har mottatt og forstått informasjon om prosjektet *"* ***Effekten av individualisert styrketrening på styrke og eksplosivitet*** *"*, og har fått anledning til å stille spørsmål. Jeg samtykker til:

☐ å delta i prosjektet " ***Effekten av individualisert styrketrening på styrke og eksplosivitet*** "

Jeg samtykker til at mine opplysninger behandles frem til prosjektet er avsluttet

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(Signert av prosjektdeltaker, dato)

Appendix IV

OLYMPIATOPPEN

SAMMEN OM DE STORE PRESTASJONENE

UiA

Informasjon om treningsprogram

Programmet er laget ut fra forskning som viser at det er gunstig å trene på egenskapen man er «dårligs» i. For eksempel om man presterte dårligst på tunge vekter, vil programmet inneholde mer tung trening. Og motsatt, hvis man var dårligst på lette vekter, vil programmet inneholde mest lette vekter.

Da denne treningen inngår i forskning, er halvparten av deltakerne tilfeldig delt inn i en kontrollgruppe, som får trening uavhengig av hva man er god eller dårlig på. Alle treningsprogrammene vil gi gunstig effekt, men det er fortsatt usikkerhet om hva som er best.

Programmet gjennomføres med 3 økter i uken. All annen trening utenom styrke kan dere styre fritt. Når det kommer til tung og eksplosiv styrke, er det kun dette programmet dere kan følge frem til neste testing (Eller eventuelle andre justeringer i avtale med trener).

Husk generell + spesifikk oppvarming før øktene. For eksempel 5-10 min jogg eller lignende dynamisk oppvarming. Spesifikk oppvarming med noen lette løft på øvelsen man skal gjennomføre er også lurt. Øvelsene gjennomføres i rekkefølgen de står i.

RIR= Reps in reserve, - Hvor mange flere repetisjoner man hadde klart i et sett når man er ferdig. - F.eks. hvis man klarer maks 8 reps i benkpress med 80kg, vil 7 reps ha en RIR=1. og 6 reps en RIR=2 osv. Lavere RIR vil si tyngre og nærmere utmattelse, hvor 0 er at man så vidt klarer siste repetisjon.

1RM= 1 repetisjon maks, tyngste man klarer å løfte 1 gang

- ***Viktig:*** ***Husk å skriv ned alle øktene man gjennomfører, og eventuelle avvik fra programmet. Skriv på notat på telefon eller ark. samles inn under testing etter treningsperioden***

For eksempel:

Dag 1: Gjennomført økter: 9

Dag 2: Gjennomført økter: 7

(Mistet 1 økt pga, sykdom)

Dag 3: Gjennomført økter: 6

(Mistet 2 økter pga skade), byttet ut øvelsen Benkpress med Skråbenk pga mangel på utstyr.

Spørreskjema før treningsperioden:
STANFORD EXPECTATIONS OF TREATMENT SCALE (SETS):

Deltaker#________ Dato: ________

Instruksjoner: Følgende spørsmål handler om treningen og treningsperioden du skal gjennomføre. Vi vil vite hvordan du tror du vil respondere på treningen. Oppgi hvor mye du er enig i hver uttalelse ved å sette et kryss over den aktuelle sirkelen. Hvis du for eksempel er veldig uenig i en påstand, kryss over sirkelen helt til venstre. Hvis du er helt enig i en uttalelse, kryss over sirkelen helt til høyre.

Svarene dine vil bli holdt anonymisert og konfidensielle og vil ikke bli sett av noen som er involvert i studien. Svarene dine på disse spørsmålene påvirker ikke treningen du får. Hvis du er usikker på noen uttalelser, vennligst gi den beste gjetning du kan. Det er ingen riktige eller gale svar.

	Helt uenig	Moderat Uenig	Litt Uenig	Verken enig eller uenig	Litt enig	Moderat enig	Helt enig
Treningen vil være veldig effektiv	○	○	○	○	○	○	○
Jeg vil prestere veldig bra etter treningsperioden	○	○	○	○	○	○	○
Jeg har sterk tillit til treningsprogrammet	○	○	○	○	○	○	○
Jeg er bekymret for negative virkninger av treningen	○	○	○	○	○	○	○

Spørreskjema etter 4-uker:
STANFORD EXPECTATIONS OF TREATMENT SCALE (SETS):

Deltaker#________ Dato: ________

Instruksjoner: Følgende spørsmål handler om treningen og treningsperioden du skal gjennomføre. Vi vil vite hvordan du tror du vil respondere på treningen. Oppgi hvor mye du er enig i hver uttalelse ved å sette et kryss over den aktuelle sirkelen. Hvis du for eksempel er veldig uenig i en påstand, kryss over sirkelen helt til venstre. Hvis du er helt enig i en uttalelse, kryss over sirkelen helt til høyre.

Svarene dine vil bli holdt anonymisert og konfidensielle og vil ikke bli sett av noen som er involvert i studien. Svarene dine på disse spørsmålene påvirker ikke treningen du får. Hvis du er usikker på noen uttalelser, vennligst gi den beste gjetning du kan. Det er ingen riktige eller gale svar.

	Helt uenig	Moderat Uenig	Litt Uenig	Verken enig eller uenig	Litt enig	Moderat enig	Helt enig
Treningen vil være veldig effektiv	○	○	○	○	○	○	○
Jeg vil prestere veldig bra etter treningsperioden	○	○	○	○	○	○	○
Jeg har sterk tillit til treningsprogrammet	○	○	○	○	○	○	○
Jeg er bekymret for negative virkninger av treningen	○	○	○	○	○	○	○

Antall gjennomførte økter:

Deltaker#________ Dato: ________

Dag:	**Dag 1:**	**Dag 2:**	**Dag 3:**
Antall økter:			

Spørreskjema etter treningsperioden:

STANFORD EXPECTATIONS OF TREATMENT SCALE (SETS):

Instruksjoner: Følgende spørsmål handler om treningen og treningsperioden du har gjennomført. Oppgi hvor mye du er enig i hver uttalelse ved å sette et kryss over den aktuelle sirkelen. Hvis du for eksempel er veldig uenig i en påstand, kryss over sirkelen helt til venstre. Hvis du er helt enig i en uttalelse, kryss over sirkelen helt til høyre.

Svarene dine vil bli holdt anonymisert og konfidensielle og vil ikke bli sett av noen som er involvert i studien. Hvis du er usikker på noen uttalelser, vennligst gi den beste gjetning du kan. Det er ingen riktige eller gale svar.

	Helt uenig	Moderat Uenig	Litt Uenig	Verken enig eller uenig	Litt enig	Moderat enig	Helt enig
Jeg mener treningen har vært veldig effektiv for min egen del	○	○	○	○	○	○	○
Jeg mener jeg har fått negative virkninger av treningen	○	○	○	○	○	○	○

Appendix V

OLYMPIATOPPEN

SAMMEN OM DE STORE PRESTASJONENE

Navn:
Idrett:
Fokus: Power/eksplosivitet med fokus på kraft

Dag 1 - Tung	**Reps x Set**						
Øvelse	**Økt 1-3**	**Økt 4-6**	**Økt 7-9**	**Mob %**	**Belastning**	**Pause**	**Kommentar**
Markløft	8 -10 x 3	5 - 7 x 3	3 - 5 x 3	80 %	1-2 RIR	2-3 min	Konvensjonell, stopp i bunn
Hoftehev	8 -10 x 3	5 - 7 x 3	3 - 5 x 3	100 %	1-2 RIR	2-3 min	En fots, høyt fotfeste
Bulgarsk utfall	8 -10 x 2	5 - 7 x 2	3 - 5 x 2	100 %	5-6 RIR	2-3 min	Antall reps = pr fot
Frontbøy	8 -10 x 2	5 - 7 x 2	3 - 5 x 2	100 %	1-2 RIR	2-3 min	Alternativt beinpress
Trapbar	5 x 2	5 x 2	5 x 2	100 %	50% 1RM	3-4 min	Eksplosivt, Hopp/opp på tå. 1-2 sek pause i bunn
Sum antall set:	12	12	12				

Dag 2 - Lett	**Reps x Set**						
Øvelse	**Økt 1-3**	**Økt 4-6**	**Økt 7-9**	**Mob %**	**Belastning**	**Pause**	**Kommentar**
Knebøy	8 -10 x 2	5 - 7 x 2	3 - 5 x 2	100 %	1-2 RIR	2-3 min	Så dypt man kommer med god teknikk
Enfots mark	8 -10 x 2	5 - 7 x 2	3 - 5 x 2	100 %	1-2 RIR	2-3 min	Bakre fot i bakken for balanse
Bulgarsk utfall	8 -10 x 2	5 - 7 x 2	3 - 5 x 2	100 %	5-6 RIR	2-3 min	
Trapbar	5 x 2	5 x 2	5 x 2	100 %	70% 1RM	3-4 min	Eksplosivt, opp på tå. 1-2 sek pause i bunn
En fots legghev	10 x 2	10 x 2	10 x 2	80 %	5-6 RIR	1-2 min	Smithmaskin / beinpress
Sum antall set:	10	10	10				

Navn:
Idrett:
Fokus: Power/eksplosivitet med fokus på hastighet

Dag 1 - Tung	***Reps x Set***						
Øvelse	***Økt 1-3***	***Økt 4-6***	***Økt 7-9***	***Mob %***	***Belastning***	***Pause***	***Kommentar***
Halve knebøy	8 -10 x 3	5 - 7 x 3	3 - 5 x 3	100 %	1-2 RIR	2-3 min	Eksplosivt opp
Knebøyhopp	5 x 3	5 x 3	5 x 3	100 %	Negativ	3-4 min	Med strikk, pause i bunn før hvert hopp. Maks innsats
Trapbar	5 x 2	5 x 2	5 x 2	100 %	50% 1RM	3-4 min	Eksplosivt, Hopp/opp på tå. 1-2 sek pause i bunn
Step up	5 x 2	5 x 2	5 x 2	100 %	10–20kg	3-4 min	Med manualer, alternere per fot
Hoftehev	8 -10 x 3	5 - 7 x 3	3 - 5 x 3	100 %	1-2 RIR	2-3 min	En fots, Lavt fotfeste
Hopp over list/kosteskaft	5 x 2	5 x 2	5 x 2	100 %	Kroppsvekt	2-3 min	Partner holder eventuelt kosteskaft oppe
Sum antall set:	15	15	15				

Dag 2 - Lett	***Reps x Set***						
Øvelse	***Økt 1-3***	***Økt 4-6***	***Økt 7-9***	***Mob %***	***Belastning***	***Pause***	***Kommentar***
Knebøyhopp	5 x 3	5 x 3	5 x 3	100 %	Negativ	3-4 min	Med strikk, pause i bunn før hvert hopp. Maks innsats
Trapbar	5 x 2	5 x 2	5 x 2	100 %	50% 1RM	3-4 min	Eksplosivt, Hopp/opp på tå. 1-2 sek pause i bunn
Hopp på kasse	5 x 2	5 x 2	5 x 2	100 %	Kroppsvekt	3-4 min	Med lite tilløp, land med utstrakte bein på kasse
Clean Pull	5 x 2	5 x 2	5 x 2	100 %	50% 1RM	3-4 min	Alternativt: Knebøyhopp
Trapphopp	5 x 2	5 x 2	5 x 2	100 %	Kroppsvekt	2-3 min	Trapphopp med armsving. 2 hopp i trapp pr repetisjon
Enfots hopp i trapp	5 x 2	5 x 2	5 x 2	100 %	Kroppsvekt	1-2 min	Hender på hofte
Sum antall set:	13	13	13				

Navn:
Idrett:
Fokus: Power/eksplosivitet med balansert fokus

Dag 1 - Tung	***Reps x Set***						
Øvelse	***Økt 1-3***	***Økt 4-6***	***Økt 7-9***	***Mob %***	***Belastning***	***Pause***	***Kommentar***
Markløft	8 -10 x 3	5 - 7 x 3	3 - 5 x 3	80 %	1-2 RIR	2-3 min	Konvensjonell, stopp i bunn
Frontbøy	8 -10 x 2	5 - 7 x 2	3 - 5 x 2	100 %	1-2 RIR	2-3 min	Alternativt beinpress
Bulgarsk utfall	8 -10 x 2	5 - 7 x 2	3 - 5 x 2	100 %	5-6 RIR	2-3 min	Antall reps = pr fot
Hoftehev	8 -10 x 3	5 - 7 x 3	3 - 5 x 3	100 %	1-2 RIR	2-3 min	En fots, høyt fotfeste
Trapbar	5 x 2	5 x 2	5 x 2	100 %	50% 1RM	2-3 min	Eksplosivt, Hopp/opp på tå. 1-2 sek pause i bunn
Trapphopp	5 x 2	5 x 2	5 x 2	100 %	Kroppsvekt	2-3 min	Trapphopp med armsving. 2 hopp i trapp pr repetisjon
Sum antall set:	14	14	14				

Dag 2 - Lett	***Reps x Set***						
Øvelse	***Økt 1-3***	***Økt 4-6***	***Økt 7-9***	***Mob %***	***Belastning***	***Pause***	***Kommentar***
Knebøyhopp	5 x 3	5 x 3	5 x 3	100 %	Negativ	3-4 min	Med strikk, pause i bunn før hvert hopp. Maks innsats
Trapbar	5 x 2	5 x 2	5 x 2	100 %	50% 1RM	3-4 min	Eksplosivt, Hopp/opp på tå. 1-2 sek pause i bunn
Hopp på kasse	5 x 2	5 x 2	5 x 2	100 %	Kroppsvekt	3-4 min	Med lite tilløp, land med utstrakte bein på kasse
Trapphopp	5 x 2	5 x 2	5 x 2	100 %	Kroppsvekt	2-3 min	Trapphopp med armsving. 2 hopp i trapp pr repetisjon
Enfots hopp i trapp	5 x 2	5 x 2	5 x 2	100 %	Kroppsvekt	1-2 min	Hender på hofte
Markløft	8 -10 x 3	5 - 7 x 3	3 - 5 x 3	100 %	1-2 RIR	2-3 min	Konvensjonell, stopp i bunn
Sum antall set:	14	14	14				

Appendix VI

Navn:
Idrett:
Fokus: Power/eksplosivitet med balansert fokus

Dag 1 - Tung	***Reps x Set***					
Øvelse	***Økt 1-3***	***Økt 4-6***	***Økt 7-9***	***Belastning***	***Pause***	***Kommentar***
Markløft	8 x 3	6 x 3	3 x 3	1-2 RIR	2-3 min	Konvensjonell, stopp i bunn
Frontbøy	8 x 2	6 x 2	3 x 2	1-2 RIR	2-3 min	Alternativt beinpress
Bulgarsk utfall	8 x 2	6 x 2	3 x 2	5-6 RIR	2-3 min	Antall reps = pr fot
Hoftehev	8 x 3	6 x 3	3 x 3	1-2 RIR	2-3 min	En fots, høyt fotfeste
Trapbar- hopp, lavt håndtak	5 x 2	5 x 2	5 x 2	50 % 1RM	2-3 min	Eksplosivt, hopp/opp på tå. 1-2 sek pause i bunn
Trapphopp	5 x 2	5 x 2	5 x 2	Kroppsvekt	2-3 min	Trapphopp med armsving. 2 hopp i trapp pr repetisjon
Sum antall set:	14	14	14			

Dag 2 - Lett	***Reps x Set***					
Øvelse	***Økt 1-3***	***Økt 4-6***	***Økt 7-9***	***Belastning***	***Pause***	***Kommentar***
Knebøyhopp	5 x 3	5 x 3	5 x 3	Negativ	3-4 min	Med strikk, pause i bunn før hvert hopp. Maks innsats
Trapbar- hopp, lavt håndtak	5 x 2	5 x 2	5 x 2	50 % 1RM	3-4 min	Eksplosivt, hopp/opp på tå. 1-2 sek pause i bunn
Hopp på kasse	5 x 2	5 x 2	5 x 2	Kroppsvekt	3-4 min	Med lite tilløp, land med utstrakte bein på kasse
Trapphopp	5 x 2	5 x 2	5 x 2	Kroppsvekt	2-3 min	Trapphopp med armsving. 2 hopp i trapp pr repetisjon
Enfots hopp i trapp	10 x 2	10 x 2	10 x 2	Kroppsvekt	1-2 min	Hender på hofte
Markløft	8 x 3	6 x 3	4 x 3	1-2 RIR	2-3 min	Konvensjonell, stopp i bunn
Sum antall set:	14	14	14			

Navn:
Idrett:
Fokus: Individualisert trening med fokus på hastighet

Dag 1 - Tung	***Reps x Set***					
Øvelse	***Økt 1-3***	***Økt 4-6***	***Økt 7-9***	***Belastning***	***Pause***	***Kommentar***
Halve knebøy	8 x 3	5 x 3	3 x 3	1-2 RIR	2-3 min	Eksplosivt opp
Knebøyhopp	5 x 3	5 x 3	5 x 3	Negativ	3-4 min	Med strikk, pause i bunn før hvert hopp. Maks innsats
Trapbar- hopp, lavt håndtak	5 x 2	5 x 2	5 x 2	50 % 1RM	3-4 min	Eksplosivt, hopp/opp på tå. 1-2 sek pause i bunn
Step up	5 x 2	5 x 2	5 x 2	10-20kg	3-4 min	Med manualer, alternere per fot
Hoftehev	8 x 3	5 x 3	3 x 3	1-2 RIR	2-3 min	En fots, lavt fotfeste
Hopp over list/kosteskaft	5 x 2	5 x 2	5 x 2	Kroppsvekt	2-3 min	Partner holder eventuelt kosteskaft oppe
Sum antall set:	15	15	15			

Dag 2 - Lett	***Reps x Set***					
Øvelse	***Økt 1-3***	***Økt 4-6***	***Økt 7-9***	***Belastning***	***Pause***	***Kommentar***
Knebøyhopp	5 x 3	5 x 3	5 x 3	Negativ	3-4 min	Med strikk, pause i bunn før hvert hopp. Maks innsats
Trapbar- hopp, lavt håndtak	5 x 2	5 x 2	5 x 2	50 % 1RM	3-4 min	Eksplosivt, hopp/opp på tå. 1-2 sek pause i bunn
Hopp på kasse	5 x 2	5 x 2	5 x 2	Kroppsvekt	3-4 min	Med lite tilløp, land med utstrakte bein på kasse
Clean Pull	5 x 2	5 x 2	5 x 2	50 % 1RM	3-4 min	Alternativt: Knebøyhopp
Trapphopp	5 x 2	5 x 2	5 x 2	Kroppsvekt	2-3 min	Trapphopp med armsving. 2 hopp i trapp pr repetisjon
Enfots hopp i trapp	10 x 2	10 x 2	10 x 2	Kroppsvekt	1-2 min	Hender på hofte
Sum antall set:	13	13	13			

OLYMPIATOPPEN

SAMMEN OM DE STORE PRESTASJONENE

Navn:
Idrett:
Fokus: Individualisert trening med fokus på kraft

Dag 1 - Tung	***Reps x Set***					
Øvelse	***Økt 1-3***	***Økt 4-6***	***Økt 7-9***	***Belastning***	***Pause***	***Kommentar***
Markløft	8 x 3	6 x 3	3 x 3	1-2 RIR	2-3 min	Konvensjonell, stopp i bunn
Hoftehev	8 x 3	6 x 3	3 x 3	1-2 RIR	2-3 min	En fots, høyt fotfeste
Bulgarsk utfall	8 x 2	6 x 2	3 x 2	5-6 RIR	2-3 min	Antall reps = pr fot
Frontbøy	8 x 2	6 x 2	3 x 2	1-2 RIR	2-3 min	Alternativt beinpress
Trapbar, lavt håndtak	5 x 2	5 x 2	5 x 2	70 % 1RM	3-4 min	Eksplosivt, opp på tå. 1-2 sek pause i bunn
Sum antall set:	12	12	12			

Dag 2 - Lett	***Reps x Set***					
Øvelse	***Økt 1-3***	***Økt 4-6***	***Økt 7-9***	***Belastning***	***Pause***	***Kommentar***
Knebøy	8 x 2	6 x 2	3 x 2	1-2 RIR	2-3 min	Så dypt man kommer med god teknikk
Enfots mark	8 x 2	6 x 2	3 x 2	1-2 RIR	2-3 min	Bakre fot i bakken for balanse
Bulgarsk utfall	8 x 2	6 x 2	3 x 2	5-6 RIR	2-3 min	Antall reps = pr fot
Trapbar, lavt håndtak	5 x 2	5 x 2	5 x 2	50 % 1RM	3-4 min	Eksplosivt, hopp/opp på tå. 1-2 sek pause i bunn
Ettbeins tåhev	10 x 2	10 x 2	10 x 2	5-6 RIR	1-2 min	Smithmaskin / beinpress
Sum antall set:	10	10	10			