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Applications of the force-velocity model in handball

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Keywords: HANDBALL, FORCE-VELOCITY, OVERARM THROWING, BENCH PRESS, STRENGTH TRAINING

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Index

Figure Index

Table Index

Abstract

Velocity of throwing is considered to be of much importance in elite level. As the assessment of individual force-velocity relationships seems to be useful to understand performance in ballistic movements we decided to apply it to handball throwing. In order to do this, we organized this thesis in two experimental and exploratory studies. The first study with the aim to develop a new and more specific methodology that could evaluate the force-velocity relationship in overarm throwing of handball players. For this, we used a set of four ball with different weights (from 433g to 747g). Nineteen handball players (Portuguese first division) performed two or three throws, replicating a 7-metre throw. Velocity was measured with a radar. From the data collected, force-velocity and power-velocity relationships were computed and individual profiles were traced. The second study aimed to explore information provided by the assessment of standard bench press throw performance through different loading magnitudes (40%,60%,70%,80%,90%), namely to determine which variables might be more informative about individual power capabilities and F-v relationships. Four handball players, playing in the Portuguese first division, performed the assessments. The developed apparatus and methodology for the first study appear to be relatively simple to use and ecologically valid to assess force-velocity and power-velocity capabilities in handball throwing, but still needs to be improved and tested with a larger sample and a wider range of balls' weight. Our results with the bench press throw showed that, when using heavy loads, there is a change of the pattern in the force-velocity relationship that demands further investigation. The different slopes obtained with bench press throws and overarm handball throwing exposed the complexity of the problematic and opens up future questions for research. Although bench press throws may be useful to assess force-velocity capabilities of the upper limbs, it seems that it doesn't really represent what happens in such a complex movement as handball throwing. This reinforces the importance of the specific and ecological methodology developed in the first study.

Keywords: HANDBALL, FORCE-VELOCITY, OVERARM THROWING, BENCH PRESS, STRENGTH TRAINING

Resumo

A velocidade de remate é considerada de grande importância no nível de elite. Como a avaliação das relações individuais de força-velocidade parece ser útil para entender o desempenho em movimentos balísticos, decidimos aplicá-la ao lançamento de andebol. Para isso, organizamos esta tese em dois estudos experimentais e exploratórios. O primeiro estudo teve como objetivo desenvolver uma metodologia nova e mais específica que pudesse avaliar a relação força-velocidade no remate em jogadores de andebol. Para isso, foi utilizado um conjunto de quatro bolas com pesos diferentes (de 433g a 747g). Dezanove jogadores de andebol (primeira divisão portuguesa) realizaram dois ou três lançamentos, replicando um lançamento de 7 metros. A velocidade foi medida com um radar. A partir dos dados recolhidos, relações força-velocidade e potência-velocidade foram calculadas e perfis individuais traçados. O segundo estudo teve como objetivo explorar as informações fornecidas pela avaliação do desempenho no supino lançado em diferentes magnitudes de carga (40%, 60%, 70%, 80%, 90%), nomeadamente para determinar quais variáveis podem ser mais informativas sobre as capacidades individuais de potência e a relação F-v. Quatro jogadores de andebol, da primeira divisão portuguesa, realizaram as avaliações. A metodologia desenvolvida para o primeiro estudo parece ser relativamente simples de usar e ecologicamente válida para avaliar as capacidades de força-velocidade e potência-velocidade em remates de andebol, mas ainda precisa de ser melhorada e testada com uma amostra maior e uma gama mais ampla de peso das bolas. Os nossos resultados com o supino lançado mostraram que, ao usar cargas pesadas, há uma mudança no padrão da relação força-velocidade que exige investigação mais aprofundada. Os diferentes declives obtidos com o supino lançado e o remate de andebol expõem a complexidade da problemática e abrem futuras questões para investigação. Embora o supino lançado possa ser útil para avaliar as capacidades de força-velocidade dos membros superiores, parece que não representa realmente o que acontece num movimento tão complexo como o remate de andebol. Isso reforça a importância da metodologia específica e ecológica desenvolvida no primeiro estudo.

Abbreviations

CMJ – Counter-Movement Jump

CSA – Cross-Sectional Area

EES – Elastic-Explosive Strength

ES – Explosive Strength

F-v – Force-velocity

IRFD – Initial Rate of Force Development

MRFD – Maximum Rate of Force Development

MU – Motor Unit

REES – Reflex Elastic-Explosive Strength

RFD – Rate of Force Development

MRFD – Maximum Rate of Force Development

MES – Maximum Explosive Strength

SJ – Squat Jump

SSC – Stretch-Shortening Cycle

1. Introduction

One of the most decisive factors for performance in a handball match is the performance in ballistic movements. These movements can be defined as maximal movement aiming to accelerate a moving mass as much as possible, attempting to achieve the highest possible velocity in the shortest time (Samozino et al., 2012). Amongst others, velocity of throwing is one factor that many authors consider to be of much importance in high level handball (Bautista et al., 2016; Manchado et al., 2013; Ortega-Becerra et al., 2018). Furthermore, velocity in handball throwing is highly influenced by both power and strength (Gorostiaga et al., 2006; Ortega-Becerra et al., 2018) and, thus, the study of the relationship power-force-velocity seems fundamental.

This relationship was first studied in the past century by Hill (1938) in isolated muscle fibres and by Wilkie (1949) in isolated human muscles but, more recently, several studies have studied it in multi-articular movements like the squat-jump (Samozino et al., 2012), counter-movement jump (Jimenez-Reyes et al., 2016) or the bench press (Sreckovic et al., 2015).

Therefore, and even though the evaluation of the force-velocity relationship in more complex movements has its limitations (as we are going to discuss in the literature review), determining the individual's force-velocity (F-v) relationship can be useful to assess the entire spectrum of an athlete's mechanical capabilities.

However, despite the increase in the number of studies about this thematic, most of them study the force-velocity relationship in standard strength training movements and not in sport specific movements. Even acknowledging the importance of this kind of evaluations, we consider that it is important to question what is the real transference between the force-velocity evaluation with a standard strength training movement and a movement that is so specific and complex as the handball throwing.

For this reason, this work was conceived in an attempt to develop a methodology that could assess the entire spectrum of the force-velocity capabilities in handball throwing and to understand if the standard procedures have a real transfer to the characteristics of such a complex movement. The bench press throw was chosen for two main reasons: because from the already tested standard procedures it is the one that presents more similarities with handball throwing, because the bench press is one of the most used strength training exercises within handball players training.

A more generic literature review about strength training and its physiological basis is going to be developed in order to deepen the knowledge about this thematic and to understand the mechanical and physiological basis of the force-velocity relationship. After a clarification about the objectives of the study, a division will be made in two different experimental and exploratory studies that meet the goals that were set in the conception of this thesis:

- Experimental Study 1 - Force-velocity Relationship in Overarm Throwing: aiming to develop a more specific methodology for the testing of the force-velocity capabilities in handball throwing.
- Experimental Study 2 - Force-velocity Relationship in Bench Press Throw and its Implications for Handball Players: aims to explore information provided by the assessment of standard bench press throw performance through different loading magnitudes, namely to determine which variables might be more informative about individual power capabilities and F-v relationships.

2. Literature Review

2.1. The Concept of Strength

Strength is recognized as an essential component of athletic performance and, thus, a capacity that must be well understood. Siff & Verkoshansky (2000) define strength as the ability of a given muscle or group of muscles to generate muscular force under specific conditions. This definition is in accordance with that of Knuttgen & Kraemer (1987) that add that the ability of a muscle to generate force is dependant both on its length and its velocity.

Zatsiorsky & Kraemer (2006) recall that, in mechanics and physics, force manifests itself through the movement and/or the deformation of one (or both) of the bodies that interact. However, the second law of Newton (F= m.a) does not represent the complexity of sports movements once that, for example, in an isometric action (no movement and, thus, no acceleration) the mechanical force would be null, even with great tension being produced in the muscle. For this reason, Badillo & Serna (2002) defines muscle strength as the capacity of producing tension in the muscle.

Therefore, it seems essential to distinguish internal force (force exerted from a constituent part of the human body on another part) and external force (force acting between an athlete body and the environment). This way we are able to differentiate muscular force, that is the force developed by a muscle, and muscular strength, that is the maximal force exerted on an external body (Zatsiorsky & Kraemer, 2006).

Siff & Verkoshansky (2000) consider that successful strength training depends on a thorough understanding of all the processes underlying the production of strength. Muscle strength is influenced by a combination of several elements and in the next chapters we present an overview of some of the morphological, neural and mechanical factors.

2.2. Neuromuscular Basis of Strength Production

2.2.1. Morphological factors

2.2.1.1. Cross-Sectional Area

Physiological cross-sectional area (CSA) represents the sum of all the fibres of a muscle, excluding all the non-contractile tissues, and is the concept that better represents the number of contractile proteins in the muscle and its potential to develop force (Mil-Homens et al., 2015). Therefore, larger muscles have the potential to produce higher forces than smaller ones (Zatsiorsky & Kraemer, 2006). However it is important to distinguish physiological cross-sectional area from anatomical cross-sectional area, as the first represents the cross-section of a muscle perpendicular to its fibres (and therefore a representation of its contractile elements) and the second corresponds to the anatomical diameter of the muscle perpendicular to the longitudinal axis (Mil-Homens et al., 2015).

Previous research suggested that not only there is a strong relationship between CSA and a greater force production (Häkkinen & Keskinen, 1989), as well as muscle CSA increases may account for 40% of the changes in strength of untrained subjects after short-term resistance training (Narici et al., 1989). These increments in strength after an increase in CSA are related to an increase in the number of cross-bridge interactions between actin and myosin in the existing sarcomeres, as well as in the newly formed ones (Suchomel et al., 2018).

2.2.1.2. Pennation Angle

The pennation angle, defined as the angle between the muscle's fascicles and the line of action has an influence in both strength and power (Cormie et al., 2011a). Larger pennation angles allow for the muscle to generate more force for two main reasons: more contractile tissue can attach to a given area of a tendon or aponeurosis (more sarcomeres can be arranged in parallel); muscle fibres can shorten less for a given tendon displacement due to the rotation of pennate muscle fibres during contraction (Muhl, 1982). Therefore, larger pennation angles not only enable the muscle to have a greater physiological cross-sectional area for a given muscle volume, but they also allow fibres to operate closer to their optimal length (Blazevich & Sharp, 2005).

On the other side, despite the potential for greater CSA due to the increase in the sarcomeres in parallel, in muscles with greater pennation angles, the fibres are shorter and, thus, have less sarcomeres in series (MacIntosh & Holash, 2000). As will be discussed in the next chapter, this has a negative impact in maximal velocity.

2.2.1.3. Fibre Length

Muscle fibre length is a function of the number of sarcomeres in series (assuming average sarcomere length). Hence, if we take into account that each sarcomere is expected to have an absolute maximal velocity (depends on the fibre type), the maximal velocity of shortening of the whole muscle fibre will be dependent on the number of sarcomeres in series (MacIntosh & Holash, 2000).

This role of the fibre length in shortening velocity is supported by the research of Kumagai et al. (2000) that reported that the vastus lateralis and gastrocnemius of highly trained male sprinters contained longer fascicles attached at smaller angles when compared to less trained sprinters. Differences in fascicle length were also found in female sprinters but when compared to a non-trained control group (Abe et al., 2001). Current literature suggests that fibres containing a larger number of sarcomeres in series possess greater shortening velocity, but longer fibres can also generate force over longer ranges of motion (Blazevich & Sharp, 2005). However, and despite recent research suggesting that eccentric training can potentiate longitudinal muscle growth (Douglas et al., 2016), more research is required to fully understand the mechanisms that lead to each type of muscle hypertrophy (Blazevich & Sharp, 2005; Cormie et al., 2011a).

2.2.1.4. Fibre type

It is possible to distinguish, in the muscle, three types of muscle fibres: type I fibres that are more resistant to fatigue and are innervated by smaller motoneurons, and thus slower; type IIx fibres that produce faster contractions once they are innervated by bigger motoneurons, but have very little resistance to fatigue; and type IIa fibres that can produce fast contractions but are more resistant to fatigue (Lieber, 2010)

Force-velocity properties of a muscle are determined by both the percentage of fast twitch fibres and their cross-sectional area (Tihanyi et al., 1982). Therefore, the maximal power output is influenced by its fibre type composition. Muscles with a greater percentage of type II fibre display higher values of power than muscles with higher percentages of type I fibres (Tihanyi et al., 1982).

These differences in power are due to the production of more force per CSA, but mainly to differences in velocity of contraction between fibre types (Lieber, 2010). The higher velocities in the muscle are directly related to the ATPase activity as type II myosin isoforms split ATPase approximately 600 times/second while type I myosin isoforms do it 300 times/second (Barány, 1967). This allows for a shorter cross-bridge cycle time and, therefore, an increase in the velocity of contraction.

2.2.1.5. Elastic Elements

According to the classic Hill's muscle model (Hill, 1938), from a mechanical point of view, the muscle can be represented not only by the contractile components, but also by viscous and elastics components. Two different types of elastic elements can be considered: in parallel (e.g. connective tissue, titin) and in series (e.g. tendon).

Therefore, besides the force generating capacities of the contractile elements, muscle performance is also influenced by the spring-like behaviours of the muscle tissues (Roberts, 2016). When the muscle and tendon are stretched, mechanical work is absorbed and stored in the elastic elements in series. This stored potential energy can be used to increase the mechanical work after the stretch (in the concentric phase of the movement) (Komi & Bosco, 1978).

Additionally, tissue stiffness (the relationship between a given force and the amount of stretch the tissue undergoes) can also influence muscle performance as its decisive for the enhancement of force transmission (Bojsen-Møller et al., 2005).

2.2.2. Neural Factors

2.2.2.1. Motor Unit Recruitment

The force produced by a muscle is related to the number and type of motor units (MUs) recruited and these are recruited in a sequence manner based on their size (smallest to largest) according to Henneman's size principle (Henneman et al., 1965). Following this principle, smaller MU's that include slow-twitch type I fibres are recruited first, at low thresholds of force, while larger MU's will only be recruited when higher forces are required. Even though, for ballistic actions, this size principle seems to hold, in these movements there are lower thresholds of MU recruitment due to fast production of force required (Van Cutsem et al., 1998).

Therefore, when training for strength or power, training should stimulate the recruitment of large MU's that include fast-twitch muscle fibres, and that could be achieved by either using heavy loads or ballistic movements (Suchomel et al., 2018).

2.2.2.2. Rate Coding/Firing Frequency

In order to increase the activation of the muscle, besides allowing a more consistent recruitment of high threshold motor units, strength training can also influence the firing frequency (or rate coding) of those MU's. This firing frequency represents the rate of impulse transmitted from the motoneuron to the muscle fibre (Sale, 2003). In fact, when the firing rate changes from its minimum to its maximum, the force that the MU can produce may be 3 to 15 greater (Enoka, 1995).

Additionally, rate of force development (RFD), a fundamental factor for performance in most sports, is highly impacted by rate coding. When the goal is to contract the muscle as fast as possible with maximum RFD, motor units begin firing at a very high frequency, followed by a rapid decline (Sale, 2003). Van Cutsem et al. (1998) research suggests that these high initial firing frequencies are linked to an increase in doublet discharges (two consecutive discharges with an interval lower than 5 ms). Furthermore, the peak firing rates attained are superior to those needed to achieve maximum force in a sustained contraction and, what these high initial firing rates provide is an increased RFD (Sale, 2003).

Research also shows that 12 weeks of ballistic training led to an enhancement in the speed of voluntary ballistic contraction due to neural adaptations like an earlier motor unit activation, a higher percentage of units firing doublets and an enhanced maximal firing rate (Van Cutsem et al., 1998).

2.2.2.3. Intermuscular coordination

While the two factors mentioned above (motor unit recruitment and rate coding) act to increase activation of the agonists, there is a simultaneous challenge to appropriately activate assisting muscles (synergists) and the muscles that oppose the action of the agonists (antagonists) (Sale, 2003). The coordinated activation of these muscles is required to generate the greatest possible force and a highly efficient movement (Sale, 2003).

Co-activation of the antagonist muscles can be counterproductive since this co-activation produces torque acting in the opposite direction of the desired movement (Cormie et al., 2011a). However, this mechanism is important to coordinate movements and maintain joint stability in order to prevent injuries (Aagaard et al., 2000). Therefore, the inhibition of agonists caused by antagonist coactivation works as protective mechanism in activities involving rapid actions (Sale, 2003).

2.2.3. Muscle Mechanics

2.2.3.1. Type of Muscle Action

In order to understand the mechanical consequences of a muscle contraction, we must take into account both the force developed by a muscle and the magnitude of the external forces that oppose it. Considering this, we can differentiate three different types of muscle action (Mil-Homens et al., 2015):

- Concentric contraction – the tension developed by the muscle is superior to the external resistance and, thus, there is a shortening of the muscle.
- Eccentric contraction – the tension developed by the muscle is inferior to the external resistance and, even though the muscle develops force in order to shorten, it stretches.
- Isometric contraction – the tension developed by the muscle is equal to the external resistance, therefore the length of the muscle doesn’t change.

However, muscle function required in human movement rarely calls for the use of these muscle actions in isolation. The successive combination of eccentric and concentric actions, form the most common muscle action that is termed stretch-shortening cycle (SSC) (Komi, 1984). This muscle behaviour allows the muscle to produce greater force or power, when compared to a concentric contraction isolated. This increase in muscle performance through the SSC is due to many factors: the storage and utilization of elastic energy, the increased amount of time available to produce force and the stretch reflexes (the force lengthening of the muscle during eccentric action causes a mechanical deformation of the muscle spindles that activates reflex mechanisms that increase muscle stimulation) (Komi, 1984).

2.2.3.2. Anatomic Joint Configuration

The anatomic configuration of a joint describes the structure and joint position in the body, as well as the locations where the muscles attach on either side of the joint (MacIntosh & Holash, 2000). For a movement to occur, the tension exerted by the muscle will generate a rotational effect on the joint. This rotational effect is called moment of force or torque (Zatsiorsky & Kraemer, 2006). The magnitude of the torque that is produced by a muscle contraction is the product of contraction force and the shortest distance from the joint centre to the line of action of the force (moment arm) (MacIntosh & Holash, 2000). Therefore, even in a muscular contraction with constant force, the torque will vary as the joint moves through a range of motion.

When a joint angle varies, the externally registered force (strength) changes due to two reasons: the muscular forces act through different moment arms; the muscle produces different tension in different lengths (Zatsiorsky & Kraemer, 2006).

2.2.3.3. Length-Tension Relationship

The muscle is able to generate different levels of force in different lengths (Gordon et al., 1966). When considering only the muscle fibre, this relationship is often illustrated in a u-shaped curve termed length-tension curve (figure 1).

In order to understand the mechanisms that lead to the production of different force in different fibre lengths, we need to understand Huxley's theory of muscle contraction: the sliding filament theory (Huxley, 1957). According to Huxley, myosin (thick) filaments slide past the actin (thin filaments) during muscle contraction. This filament sliding occurs by cyclic attachment and detachment of myosin on actin filaments, creating a, usually termed, cross-bridge. Contraction occurs when the myosin pulls the actin filament, detaches from it and creates a force (stroke) to bind to the next actin molecule.

Therefore, the optimal length for force production exists when the length of the sarcomere allows for an optimal overlap of the actin and myosin filaments. If, at this point of maximal cross-bridge interaction, tension is maximal, force production is impaired when (Gordon et al., 1966):

- Sarcomere length is decreased causing an overlap of the actin filaments and, thus, decreasing the number of cross-bridges (point a in the figure);
- Sarcomere length is increased, decreasing the number of possible interactions between actin and myosin filaments (point c in figure 1);

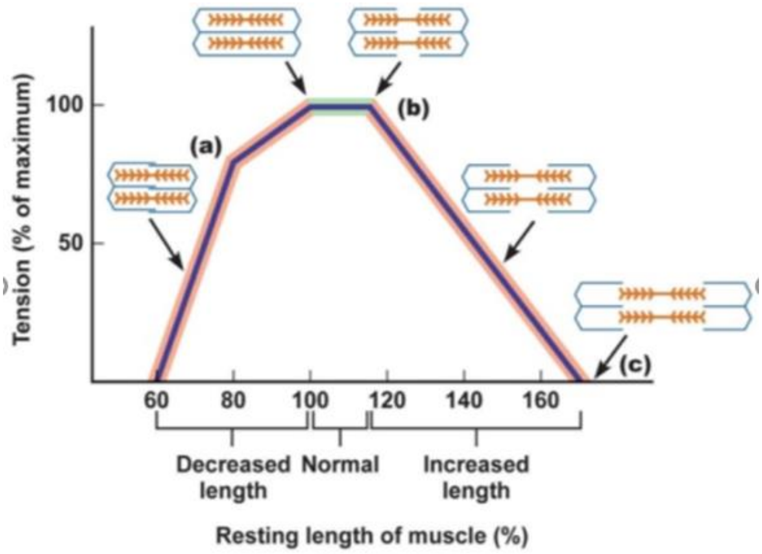


Figure 1. Length-tension relationship in the sarcomere. Adapted from Gordon et al. (1966)

However, when the length of the muscle increases and the muscle stretches, there is an increase in total tension. Even though the active tension decreases (due to less actin-myosin interaction), the passive tension caused by the elastic potential in the elastic elements in parallel (connective tissue, titin) originates an in increase in total tension of the muscle (Lieber, 2010).

2.2.3.4. Force-Velocity Relationship

The force-velocity and power-velocity relationships have been studied at different levels of organization: molecular level, single cell level, whole muscle or single and multi-joint movements. Furthermore, these relationships can be studied by controlling one of the variables and measuring the other: isotonic contractions for controlled load (force) and isokinetic experiments for controlled velocity (MacIntosh & Holash, 2000).

Regardless of the method, the inverse, hyperbolic, relationship between force and velocity described by Hill (1938) can be observed in concentric muscle contractions (figure 1). Hill described mathematically this relationship in which, as velocity of shortening increases, the ability to produce force decreases. In order to understand this inverse relationship, we have to go back to Huxley's (1957) theory of muscle contraction and, specifically to the formation of cross-bridges. As discussed in the previous chapter, the muscle contraction depends on the interaction between myosin and actin and, hence, on the number of interactions (cross-bridges) between the two filaments. Since it takes a certain amount of time for cross-bridges to attach and detach, when velocity of shortening increases, the number of attached cross-bridges decreases and, thus, force production decreases as well (Lieber, 2010).

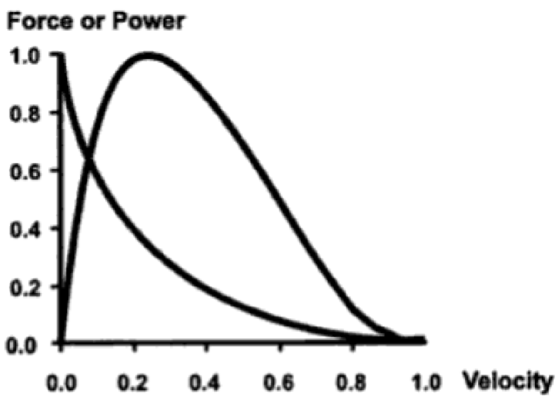


Figure 2. The force-velocity and power-velocity relationships (MacIntosh & Holash, 2000, p. 194)

Mechanical power output is a product of force and velocity, therefore, peak power output is defined by this force-velocity relationship and, consequently, by the maximal force and maximal shortening velocity of the muscle (MacIntosh & Holash, 2000). Hence, all the factors mentioned in the previous chapters (morphological, neural, mechanical) will influence both the force-velocity relationship and peak power outputs.

Additionally, measurements of the force-velocity relationship in vivo, in multi-joint movements, have been conducted for the lower limbs (Jimenez-Reyes et al., 2016; Samozino et al., 2008) and the upper limbs (Rahmani et al., 2018). It is important to understand the hyperbolic relationship refers to studies in isolated fibres (Hill, 1938) or even isolated human muscles (Wilkie, 1949) and that, in multi-joint movements, this relationship is almost linear rather than hyperbolic (Jaric, 2015). According to Bobbert (2012), this quasi-linear shape is explained by mechanical factors such as segmental dynamics.

Although in vivo measurements are complicated by mixed-fibre composition, architectural characteristics, anatomical joint configuration and levels of neural activation, the information obtained from these experiments is essential to understand maximal power production during sportive movements (Cormie et al., 2011a).

2.3. The Different Expressions of Strength

The term strength has been employed in various ways by sports coaches, strength coaches, athletes, and the lay public as well. The term is commonly used to refer to the generic ability of being strong, but it only offers useful information to coaches if the strength component concerned is specified.

It is important to be aware that the categorization of strength and its capabilities in different types of strength can be somewhat restrictive given that they are interrelated, in their production and development, and that they are not displayed separately but are components of every movement (Siff & Verkoshansky, 2000).

Nevertheless, the knowledge of the different ways an athlete can express strength and the particularities of each component seem fundamental to understand strength training.

2.3.1. Maximum Strength

Knuttgen & Kraemer (1987) propose that the term strength should be employed to refer to the "maximal force a muscle or a muscle group can generate at a specific velocity". However, the development of force varies depending on the type of muscle action (concentric, eccentric and isometric), the velocity of the action (for dynamic contractions) and the length of the muscle. Therefore, it is not possible to evaluate strength under a single set of conditions as there are many variables involved (Knuttgen & Kraemer, 1987).

For this reason, and even though the levels of strength will still differ depending on the velocity of the action and length of the muscle, the different expressions of maximal strength can be organized according to the type of muscle action (Badillo & Ayestarán, 1997; Knuttgen & Komi, 1992):

- Maximum isometric strength – The maximum voluntary contraction against an immovable resistance. For comparative purposes, the measurements must be performed when the muscle or muscle groups are at similar lengths.
- Maximum eccentric strength – It is defined as the maximum capacity of muscular contraction against a resistance that moves in the opposite direction of the force applied by the subject. It depends on the velocity of stretching and is usually evaluated using a percentage of the maximum isometric strength.
- Maximum concentric strength – The maximum capacity of muscle contraction in a shortening action, when the load moves in the same direction that the force is produced.

Badillo & Ayestarán (1997) add that we should also consider the following terms:

- Maximum dynamic strength – Maximal expression of strength when the subject is only able to move the resistance once (commonly termed 1RM). It refers to the peak force obtained during the dynamic action (e.g. in a squat or bench press). While the authors recognize that in these movements there is a stretch-shortening cycle, they consider that, due to the high loads and low velocity, the force produced doesn’t depend on the elastic properties.
- Maximum relative dynamic strength – It is manifested against lower resistances than the maximum dynamic strength and corresponds to the maximal value of strength for each percentage of the maximum isometric

strength. Its improvement should be an important objective of training as this is the main expression of strength during competition.

In figure 3 we can observe how the evaluation of maximal strength has a different meaning according to the type of muscle action. When a subject produces force against a certain resistance, the magnitude of that resistance will determine the maximal force he/she can produce (maximal relative dynamic strength). If we progressively increase the load, we are going to achieve a load that the subject can no longer move, performing an isometric action (represented by the solid line). If, after attaining maximal isometric strength, we keep increasing the external load, he/she will be forced to perform an eccentric muscular action, producing even more force (Mil-Homens et al., 2015; Schmidtbleicher, 1992)

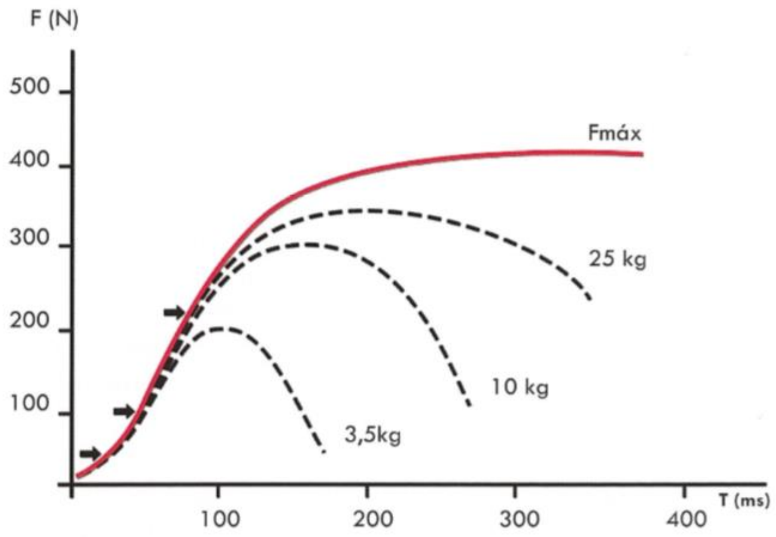


Figure 3. Graphic representation of a muscular strength evaluation of the elbow extensor muscles against different resistances. Adapted from Schmidtbleicher (1992, p. 382)

Some authors also consider other concepts as absolute strength, that is the theoretical potential of strength that isn't possible to manifest voluntarily, but through electrical stimulation or extreme psychological situations (Badillo & Ayestarán, 1997; Siff & Verkoshansky, 2000).

However, it is important to notice that the term absolute strength is also employed to define the maximal strength that an athlete can produce, regardless of their body weight. Accordingly, the relative strength is the strength produced per unit of body mass (Mil-Homens et al., 2015).

2.3.2. The time and velocity factors

If we accept the definition proposed above that strength refers to the "maximal force a muscle or a muscle group can generate at a specific velocity", we are not considering the time factor. And in a big part of sportive movements, performance doesn't depend so much on high levels of strength (in its maximum expression) but on how fast the athlete can produce strength (Schmidtbleicher, 1992).

In fact, a well-trained athlete would need 800-900ms to produce maximal strength in a lower limb extension movement. On the other hand, the ground contact of a good sprinter takes only 80-100ms and the great majority of displacements in team sports last between 250 and 400ms (Schmidtbleicher, 1992; Zatsiorsky & Kraemer, 2006). Additionally, there is a negative correlation between the maximal isometric strength and movement speed meaning that, with low external loads, the influence of maximal strength decreases (Schmidtbleicher, 1992).

There is no universally accepted classification and definitions for the various forms of expression of strength. Furthermore, when the subject is speed-strength, explosive strength or power, the literature is unclear, confusing and even contradictory. However, and despite all the confusion with the terminology, several authors agree that two mechanical properties of the muscle are paramount and should be maximized to optimize performance (Badillo & Ayestarán, 1997; Carvalho & Carvalho, 2006; Mil-Homens et al., 2015; Newton & Kraemer, 1994):

- The ability to develop more force in less time – expressed in the force-time curve
- The muscle's ability to continue producing high levels of force as its velocity of shortening increases – expressed in the force-velocity curve.

These abilities are conceived by some authors as two components of a more general and embracing concept. However, there is no consensual terminology in the literature and several authors use generic concepts as speed-strength (Siff & Verkoshansky, 2000), power (Zatsiorsky & Kraemer, 2006), explosive muscular power (Newton & Kraemer, 1994) or fast strength (Mil-Homens et al., 2015) when referring to the training of this ability to produce strength fast.

Despite the differences between the two concepts mentioned above, it is important to notice that any modification in the force-time curve is reflected in the force-velocity curve, and vice versa (Badillo & Ayestarán, 1997).

Therefore, the understanding of the force-time and force-velocity curves is fundamental to understand the different expressions of strength and its training.

2.3.2.1. Force-Time Curve/RFD

Every movement can be represented in the force-time curve and it can be used for either static or dynamic measures. Any positive modification happens when the curve moves left, meaning that the subject is able to produce the same amount of force in less time or that in the same time he/she produces more force (Badillo & Serna, 2002).

In figure 2, two hypothetical force-time curves for two different athletes are represented. Athlete B clearly presents higher levels of maximum strength in this given movement. However, if time to produce force is limited, like in the majority of sports, athlete A has a better performance, as he can produce forcefaster.

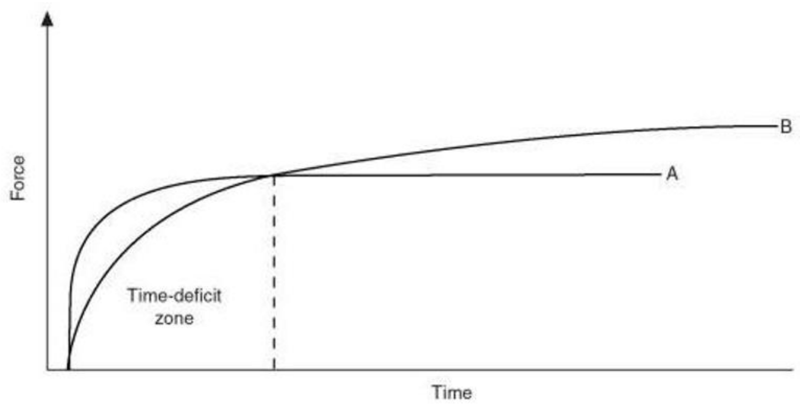


Figure 4. Force-time histories for two athletes (Zatsiorsky & Kraemer, 2006, p. 28)

But what is the correct term that defines the result of the relationship between the force produced and the time needed for its production? In the literature, we can find different terminologies, and there is no consensual term to define this relationship.

One of the most used expressions is explosive strength (ES) and it is defined as the ability to exert maximal forces in minimal time (Badillo & Ayestarán, 1997; Siff

& Verkoshansky, 2000; Zatsiorsky & Kraemer, 2006). It is expressed in Newtons per second (N.s^{-1}).

Another term commonly used in the literature is rate of force development (RFD) and it is defined as the proportion, rate or velocity of force production (Badillo & Serna, 2002; Schmidtbleicher, 1992). Rate of force development can be evaluated by the slope in the force-time curve, from the beginning to any point of the curve (Carvalho & Carvalho, 2006). However, the evaluation of RFD in different parts of the curve has different meanings and, again, the terminology varies in the literature.

Although it is possible to measure RFD in different points of the force-time curve, there is a moment in which the rate of force production per time unit is maximal. This moment is reflected by the maximal slope of the curve (Siff & Verkoshansky, 2000). The term "maximum rate of force development" (MRFD) is, apparently, the most consensual among the experts and across the scientific literature, to describe this point of the curve (Badillo & Serna, 2002; Kraemer & Newton, 2000; Mil-Homens et al., 2015; Schmidtbleicher, 1992; Siff & Verkoshansky, 2000).

However, and as mentioned above, the term explosive strength is widely used, not only in the scientific literature but also amongst strength coaches and sports coaches in general. Nevertheless, the meaning of ES is not so consensual as the meaning of RFD. While a big part of researchers consider that ES and RFD represent the same capacity and, thus, the equivalent of MRFD is "Maximum Explosive Strength" (MES) (Badillo & Serna, 2002; Carvalho & Carvalho, 2006; Mil-Homens et al., 2015), some experts in the subject as Siff & Verkoshansky (2000) or Zatsiorsky & Kraemer (2006) conceive explosive strength by itself as the maximum production of force per time unit and, therefore, a concept identical to MRFD.

Additionally, Siff & Verkoshansky (2000), in their highly acknowledged book "Supertraining", identify different phases of the force-time curve:

- Starting Strength – ability of the muscles to develop force at the beginning of the working contraction before external movement occurs. It is always produced under conditions of isometric muscle action. Schmidtbleicher

(1992) uses the term "Initial Rate of Force Development" (IRFD) when referring to the same ability.

- Acceleration Strength - ability over time to quickly achieve maximal external force while developing muscle tension isometrically or at the beginning of a dynamic contraction.
- Explosive Strength – As mentioned above, it is the portion of maximal slope of the curve, hence it is the part where RFD is also maximal. Also termed as Maximum Rate of Force Development (Schmidtbleicher, 1992).

According to Schmidtbleicher (1992), when the external resistance is low (less than 25% of maximal strength), the initial part of the curve, IRFD, is decisive. This component is of much importance in sports like boxing or karate. On the other hand, as resistance increases (e.g., throwings), MRFD becomes more relevant. The same author adds that in movements with a duration of 250 ms or less, RFD is decisive, while in movements that require more time to complete, the influence of maximal strength increases.

2.3.2.2. Force-Velocity Curve/Muscle Power

The force-velocity curve is, naturally, associated with the concept of power (P). In a mechanical perspective, power (W) is defined as the amount of produced work (J) per time (t). Once the mechanical work is the product of force and distance, we have that P=F.d/t and, thus, power is the product of force and velocity (P=F.V) (Knuttgen & Kraemer, 1987).

The quantitative relationship between force and velocity and the mechanisms of why there is an inverse relationship between force produced and the velocity of muscle shortening were already discussed above. It is important to remember that, even though we refer to this relationship as the force-velocity curve (due to its shape when studied at fibre level), in multi-joint movements this is an almost linear relationship (Jaric, 2015).

In one end of the curve, we have a point where the force is maximal and the velocity is null, while in the other end we have the opposite, the velocity is maximal and the force is null. Between the two ends, there is a point where power is maximal. In isolated muscle fibres, it is maximal for values of around 30% of maximal force and maximal velocity as shown in figure 3 (Kaneko, 1984).

However, for multiarticular movements, these values will depend on the nature of the movement (Cormie et al., 2011b).

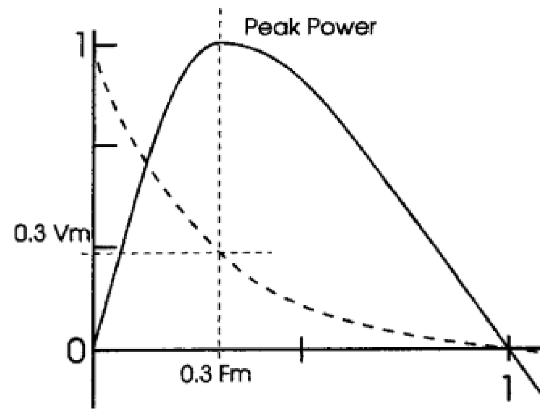


Figure 5. Force-velocity (dashed line) and Power-velocity curves (Kraemer & Newton, 2000, p. 347)

Maximal power is fundamental for performance in sportive movements that have the goal of producing high velocity at release or impact (Kraemer & Newton, 2000). Mil-Homens et al. (2015) define maximal power as the capacity of producing high levels of force as the velocity of shortening increases. The same authors state that power training is no more than the constant search for optimization of the relationship between force and velocity.

Several authors consider that different training loads should be applied in order to maximize muscular power and, therefore, different training zones are distinguished in the force-velocity curve (Cormie et al., 2011b; Kraemer & Newton, 2000; Mil-Homens et al., 2015; Siff & Verkoshansky, 2000):

- Zone of maximal force influence – high resistances and low velocities.
- Zone of maximal velocity influence – high velocities against low resistances.
- Zone of power – usually divided in two different zones:
    - Strength-speed zone – both speed and strength are important, but there is an emphasis on the strength component.
    - Speed-strength zone – both speed and strength are important, but there is an emphasis on the speed component.

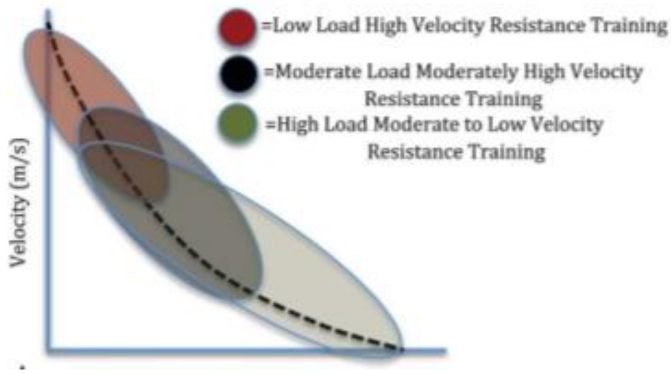


Figure 6. Different training zones for maximal power optimization. Adapted from (Haff & Nimphius, 2012, p. 7)

It is important to understand that, although both force-time and force-velocity curves have their own characteristics, they are not dissociated. In fact, if we compare the positive effects that we seek in both curves, we observe that they are related: producing more force in less time (force-time curve) is equivalent to producing more force at higher velocities (force-velocity curve) (Badillo & Serna, 2002). The adaptations we achieve in the force-time curve are reflected in the force-velocity curve, and vice-versa, as represented graphically in figure 7.

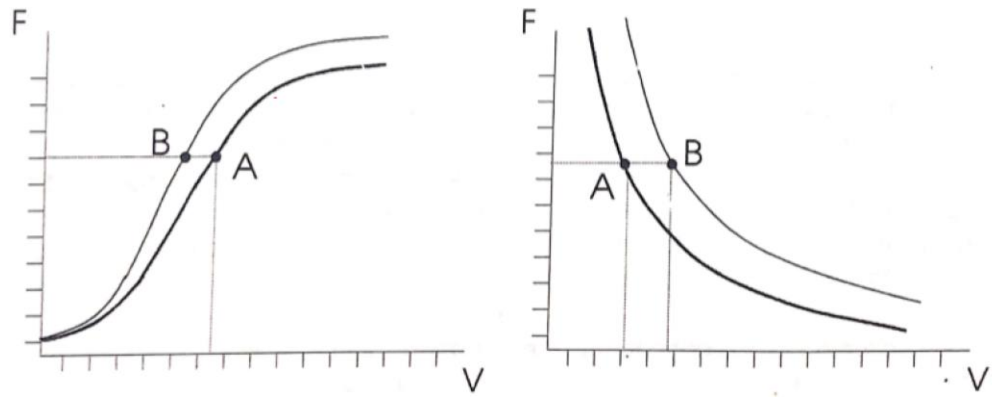


Figure 7. The points A and B represent the theoretical curves before and after training, respectively. The improvements in on curve is reflected in the other. Adapted from Badillo & Ayestarán (1997, p. 49)

2.3.3. Reactive Strength

It is necessary to emphasize that a great majority of sportive movements don't involve isolated forms of muscle action (isometric, concentric or eccentric). In movements like running or jumping, for example, the body segments are subjected to impact forces. In these phases, there is an eccentric contraction prior to the concentric (Komi, 1984). This combination of contractions is called stretch-shortening cycle (SSC) and according to Komi (1984) this muscle behaviour allows the final action (concentric contraction) to take place with greater force or power output.

Although there is a relationship with other expressions of strength, there is a low correlation between the performance in the SSC and maximum strength (Mil-Homens et al., 2015). Therefore, the SSC has been associated with the expression of strength termed Reactive Strength.

The superior performance in the SSC is observed by Komi & Bosco (1978) when comparing jump heights in the squat jump (SJ) and countermovement jump (CMJ). The researchers observed that the jump height in the CMJ (the athlete performs a preparatory dip before jumping upwards) was 18 to 20% higher comparing to the SJ (purely concentric jump initiated from a crouch position). This superior performance in the SSC can be explained by both mechanical and neural factors (Mil-Homens et al., 2015).

Badillo & Ayestarán (1997) and Schmidtbleicher (1992) differentiate two types of reactive strength:

- Elastic-Explosive Strength (EES) – is expressed in long SSC’s (ground contact time superior to 250 ms), usually characterized by wide movements. In this movements, besides the capacity of producing high levels of force, through the instant recruitment and synchronization of a greater number of motor units, there is an additional elastic component due to the previous stretching (eccentric phase) of the muscle, storing kinetic energy that is going to be released in the concentric phase in the form of mechanical energy. This manifestation of reactive strength is characteristic of movements like the jump shot or the defensive block in handball.
- Reflex Elastic-Explosive Strength (REES) – expressed in short SSC’s (ground contact time inferior to 250 ms), characterized by movements with smaller angular displacements. In addition to the factors referred in the EES, there is an important neural factor, the myotatic reflex (or stretch reflex) that intervenes due to the fast transition from the eccentric to the concentric phase.

2.3.4. Endurance Strength

Endurance strength can be defined as the neuromuscular capacity to delay the appearance of fatigue in medium or long-term efforts, minimizing the decrease of muscular performance (Mil-Homens et al., 2015; Siff & Verkoshansky, 2000).

Zatsiorsky & Kraemer (2006) identify two ways of evaluating endurance strength: absolute endurance (ignores the individual differences in maximum strength) and relative endurance (measured according to the individual levels of maximum strength).

Accordingly, the absolute indices of endurance strength show a strong correlation with maximum muscular strength meaning that stronger individuals can repeat a vigorous exercise more times than weaker ones (Zatsiorsky & Kraemer, 2006). To illustrate this relationship, Mil-Homens et al. (2015) use the example of a rower: if, at a certain velocity, the rower needs to produce 500 N of force per row and his/her maximum strength (for that movement) is 1000 N, then he/she is working at 50% of his/her maximum. However, if his/her maximal strength was only 750 N, he/she would have to work at 67% of his/her maximum, increasing the levels of effort and, consequently, fatigue.

Badillo & Ayestarán (1997), on the other side, don't conceive endurance strength as an expression of strength by itself. For these authors, endurance strength should only be conceived as the capacity to delay the appearance of fatigue of one of the expressions of strength discussed above. Therefore, endurance strength is viewed as the capacity to maintain performance with time during the expression of, for example, maximal strength, explosive strength or even different types of strength combined.

2.3.5. Categorization of the Expressions of Strength

As mentioned throughout the previous chapters, there is not a consensus about the appropriate terminology for the different components of strength. This may be due the fact that all the forms of expressing strength are interrelated and they hardly manifest separately (Siff & Verkoshansky, 2000). However, being aware of the importance of organizing and clarifying the terminology within the scope of this work, the use of the following classification is purposed, based on the literature reviewed in this chapter.

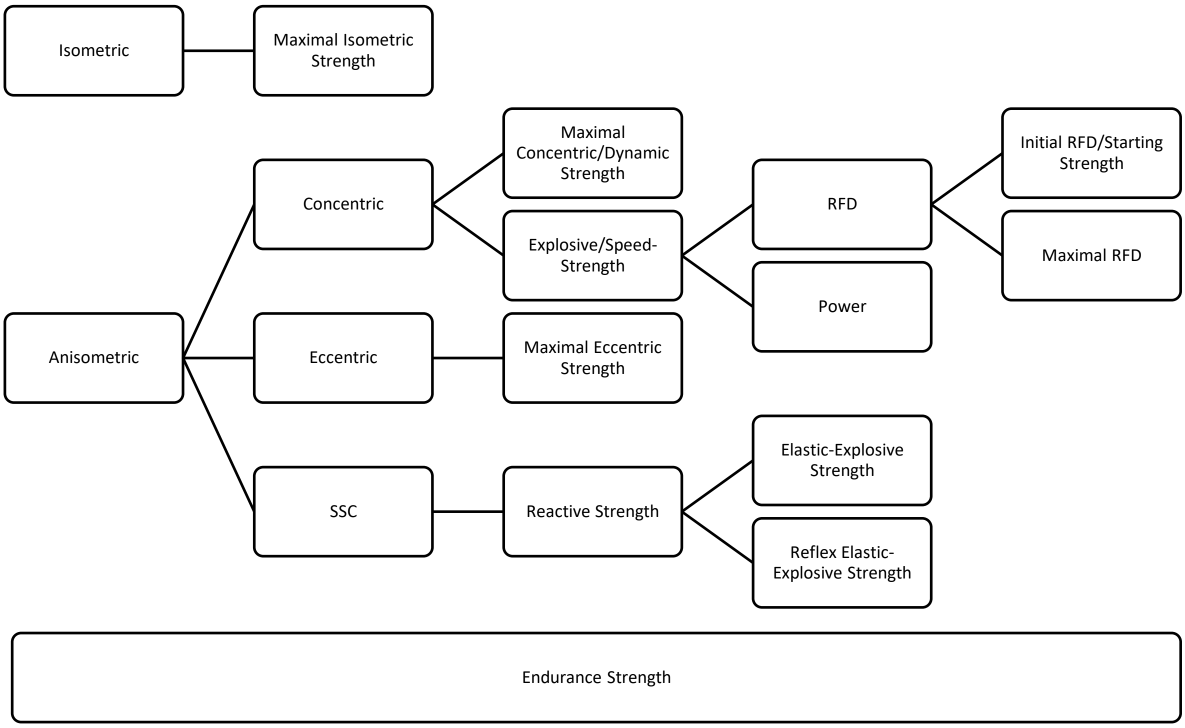


Figure 8. Proposal for the categorization of the different expressions of strength

2.4. Training for Power

Power was already defined above as the product between force and velocity (Knuttgen & Kraemer, 1987) and associated with Hill's (1938) force-velocity curve. Furthermore, different training zones have been specified for its training. However, and given the purpose of the current thesis and the wide discussion in the literature on this topic, namely about the optimal training methods and appropriate loads, a more in-depth review of methods for power training was considered relevant.

Despite the low velocities of movement, several authors suggest that training with heavy loads is the optimal method for power training. One of the arguments used is that, due to the correlation between strength and power, with the improvement in maximal strength through heavy loads training, maximal power also increases (Moss et al., 1997; Widrick et al., 2002). Additionally, according to the size principle, high threshold motor units that innervate type II muscle fibres are only recruited with exercises that require near maximal force output (Henneman et al., 1965; Schmidtbleicher & Haralambie, 1981). However, and even though strength is directly related to power, in athletes that already present high levels of strength, training with heavy loads it's not effective in increasing maximal power (Cormie et al., 2011b; Newton & Kraemer, 1994).

On the other hand, Behm (1988) suggests that an optimal method for power training and performance improvements is training with light loads, as high tensions inhibit the capacity of generating high velocities. This is supported by the studies of Wilkie (1949) that show that velocity decreases as load increases. Training with this type of loads enables the athletes to train, not only with velocities similar to competition contexts, but also to include more specific exercises (with movement patterns closer to the sport) (Cormie et al., 2011b; McBride et al., 2002). Additionally, and although in ballistic movements the size principle is preserved, there is a lowering in the recruitment threshold and an enhanced firing rate of the motor units (Van Cutsem et al., 1998). Therefore, ballistic and plyometric training is recommended for athletes of sports that require high levels of power and high-velocity movements against low resistance as sprints, jumps or throws (Kawamori & Haff, 2004; Winchester et al., 2008). It is important to note, however, that this positive adaptations are only relevant when using ballistic or plyometric exercises and that the use of light loads with traditional resistance training exercises would not promote an adequate stimulus for adaptation (Newton & Kraemer, 1994).

2.4.1. The Optimal Load

The load that elicits maximal power outputs in a specific movement is often referred to as the optimal load (Cormie et al., 2011b; Haff & Nimphius, 2012; Kawamori & Haff, 2004). It has been suggested that training with this optimal load is an effective method to promote increases in maximal power output for a specific movement. However, as improvements in power are most pronounced at the load used in training, this methodology may impact sports performance by limiting the ability of an athlete to maximize power output under a variety of loaded conditions (Kawamori & Haff, 2004; McBride et al., 2002; Moss et al., 1997).

Furthermore, from a methodological point of view, attempts to identify athlete's individual optimal loads often produce variable results. For example, Cormie, McCaulley, Triplett, et al. (2007) measured the optimal loading for different lower-body resistance exercises and found that this load ranged from 0% of squat 1RM in jump squat to 56% in the squat and 80% in the power clean (mean values). In addition to the differences between exercises, the measured peak power differs if the athlete's bodyweight is considered, meaning that different bodyweights and relative strength are factors that influence this optimal loading (McBride et al., 2011).

Training at a single relative load is also unlikely to elicit improvements in other regions of the force-velocity curve and, thus, employing a variety of loads appears to be the best approach if the athlete's goal is to produce the highest velocity (and therefore power) at any given load during competition or training (Cronin & Sleivert, 2005; Haff & Nimphius, 2012).

2.4.2. Mixed Methods Approach

The benefits and limitations of training with either heavy or light loads were mentioned above. If, on the one hand, using light loads enhances muscular performance in the high-velocity part of the curve, the use of heavy loads improves it in the high-force portion of the curve, and both are important in maximizing power (Cormie et al., 2011b; Haff & Nimphius, 2012; Suchomel et al., 2018). These changes in different portions of the curve are illustrated in figure 9.

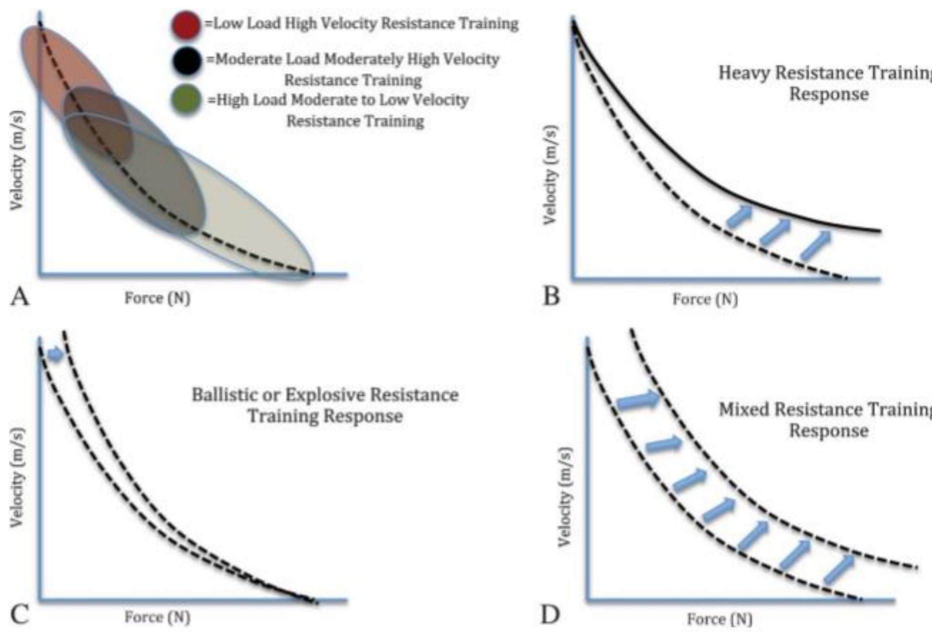


Figure 9. Theoretical representation of the adaptations in the force-velocity curve after resistance training with heavy loads (B), ballistic training with light loads (C) and training with a combination of loads (D) (Haff & Nimphius, 2012, p. 7)

Therefore, a mixed methods approach, using different types of loads, allows for a superior increase in maximal power output and a greater transfer of training effect to performance as there is an all-round improvement in the force-velocity relationship (Cronin & Sleivert, 2005; Newton & Kraemer, 1994). This approach finds significant support in the literature since, when compared to high force or high velocity training, superior enhancements were found, not only in maximal power output for different loads but also in a wide variety of athletic performance variables requiring strength, power and speed (Cormie, McCaulley, & McBride, 2007; Harris et al., 2000; Newton et al., 1999; Toji & Kaneko, 2004).

Nevertheless, Suchomel et al. (2018) underline that the training loads should complement the exercises that are being used. As an example, heavier loads maybe be prescribed using core exercises (e.g., squats, presses, and pulls) and certain weightlifting movements, while lighter loads should be prescribed to emphasize higher velocities during ballistic movements.

Once all the different types of training seem to play their role in the development of athletic performance, how should we organize training and how can we know when it's the right time to introduce a different stimulus?

As discussed above, the importance of maximal strength extends beyond the ability to produce maximal force. Suchomel et al. (2018, p. 5) perceive strength as the "vehicle driving the enhancement of several key performance variables, particularly RFD and power". Mil-Homens et al. (2015) consider that maximal strength is the basic component that influences all the other expressions of strength and, thus, it should be developed in the early phases of training. Moreover, there is evidence that improvements in power outputs following ballistic resistance training are greater in stronger subjects (Cormie et al., 2010; Stone et al., 2003).

Accordingly, some reputable authors as Badillo & Serna (2002) or Siff & Verkoshansky (2000) propose periodization models in which increases in muscle mass and the development of maximal strength (heavy loads) is performed at the beginning of training cycles while ballistic exercises with loads and velocities closer to competition are performed at a later stage. An example of this logical progression is illustrated in figure 2.

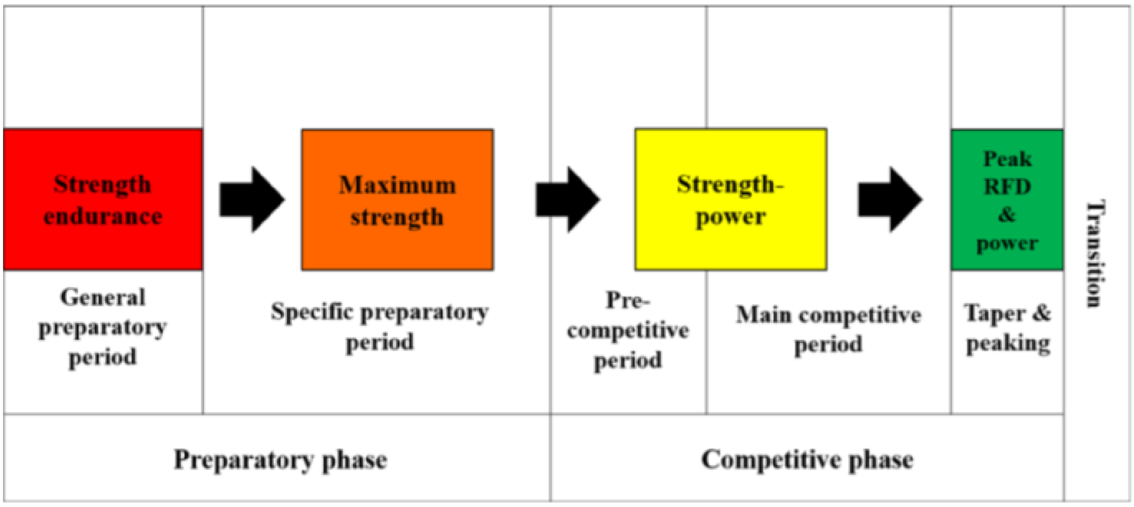


Figure 10. Single-targeted block periodization model for the development of strength-power capacities (Suchomel et al., 2018, p. 5)

Despite allowing a logical organization, the model presented above doesn't consider one of the basic training principles, the principle of individualization. According to this principle, a training program should account for the differences in athletes' capacity for adaptation that is influenced by factors as current fitness, training history or genetics (Kasper, 2019). It was mentioned above that individuals with different strength levels would respond differently to strength or power training. Hence, when planning strength training, we must consider the athlete's individual profile, his qualities and his deficits (Jimenez-Reyes et al., 2017). But how can we evaluate each athlete's profile?

2.4.3. Force-Velocity Profiling

According to Samozino et al. (2012), part of this individualization can be achieved by accessing each athlete's force-velocity (F-v) profile. These authors studied ballistic performance in the lower limb neuromuscular system and concluded that two individuals with the same levels of maximal power and the same push-off distance (centre of mass height at take-off) can attain different performances. These differences are associated with the different F-v profiles. A F-V profile shows the existing balance between the force and speed of an athlete for a specific movement or action. This was first tested by jumping with different loads to determine the slope of the F-v (Samozino et al., 2008; Samozino et al., 2012). Therefore, for each individual, there is an optimal profile that maximizes ballistic performance and that represents the optimal balance between the force and velocity capacities for each movement (Samozino et al., 2013; Samozino et al., 2012). From the difference between the real profile and the optimal profile, it is possible to determine the imbalances in the F-v relationship and, consequently, the deficits of strength or velocity for each athlete (Samozino et al., 2012).

The identification of this imbalances and deficits allows the coaches to program training (and its loads) according to the individual needs of their athletes and performance demands: an athlete that shows an imbalance in favour of force should improve his/her velocity capabilities by training with light loads; an athlete that has an imbalance in favour of velocity should train with heavy loads in order to improve his/her force capabilities. This logic of programming strength training was tested by Jimenez-Reyes et al. (2017) and improvements in ballistic performance were observed through an optimization of the F-v profile. Thereupon, the authors concluded that this method of training (focusing on individual needs) is more efficient in improving jumping performance if comparing to traditional strength training that is usually common to all athletes.

In order to optimize strength training, the mechanical capacities of the muscle can then be studied "through loaded multi-joint tasks that provide relatively simple linear F–V and parabolic P–V relationships, and those same tasks can be developed into a relatively simple and ecologically valid test of strength-, power-, and velocity-producing capacities of the muscular system" (Sreckovic et al., 2015, p. 10).

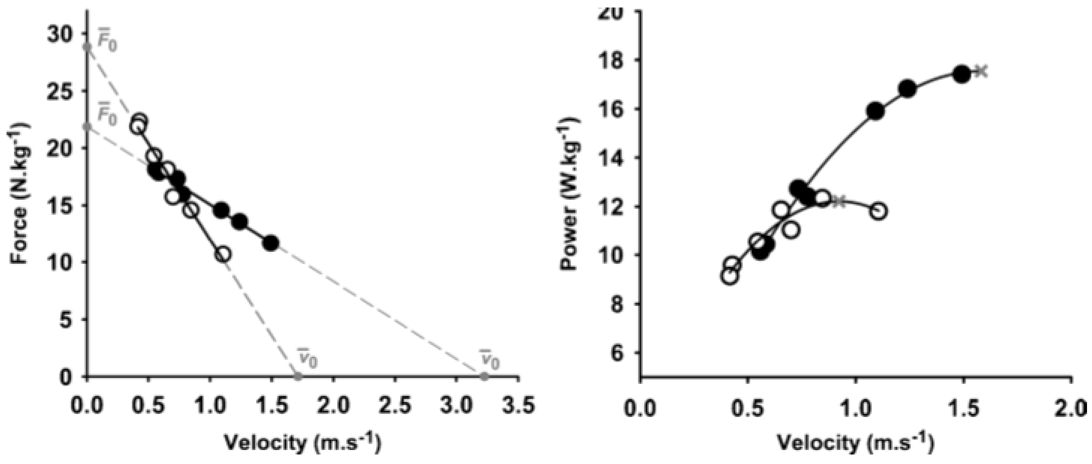


Figure 11. Typical force-velocity (left image) and power-velocity (right image) profiles for two individuals. The subject 1 (empty circles) presents a lower maximal power and a force-oriented profile, while the subject 2 (filled circles) has a velocity-oriented profile (Samozino et al., 2012, p. 316)

3. Force-velocity Relationship in Overarm Throwing

3.1. Abstract

Velocity of throwing is one of the most determinant abilities in handball performance (Manchado et al., 2013; Ortega-Becerra et al., 2018). As it is influenced by both power and strength (Gorostiaga et al., 2005), it seems important to understand the force-velocity relationship in this movement.

Research about force-velocity relationships in multi-joint movements is growing and the importance of knowing the individual force-velocity profiles of the athletes seems to be of much importance (Jimenez-Reyes et al., 2017; Samozino et al., 2012). However, this research focus mainly on the study of this relationship in standard strength training movements and its transference for a specific and complex movement like handball throwing is arguable.

In an attempt to contribute to the filling of this gap, we developed a more ecological methodology with the aim of assessing force-velocity relationships in handball. For the data collection, four handballs (size 3) with different weights were used: 433 kg, 546 kg, 607 kg and 747 kg. Nineteen handball players of the Portuguese first division were organized in sets of four players to perform the throws randomly with each of the four different balls, with one minute and thirty seconds of rest between attempts. The participants were asked to replicate a 7-meter throw (and thus, without lifting one of their feet) with their maximal shooting velocity.

The developed apparatus and methodology appear to be relatively simple to use and ecologically valid to assess force-velocity and power-velocity capabilities in handball throwing, but still need to be improved and tested with a larger sample and a wider range of balls' weight. However, this was an exploratory study and the methodology still has some faults and limitations

Our findings also showed that the majority of the evaluated players would produce higher standing-throw power if the ball was heavier than the official size 3, meaning that they have a speed deficit and a more force-oriented profile.

3.2. Introduction

As mentioned both in the main introduction and in the literature review, the force-velocity relationship has been deeply studied both in its physiological basis and, more recently, in its applications to sports science. These applied studies showed that, not only it is possible to obtain an individual profile through the evaluation of performance in different loading conditions (Cuk et al., 2014; Jaric, 2015; Jimenez-Reyes et al., 2016; Samozino et al., 2012) but also that training according to each athlete's profile is more effective to improve performance in ballistic movements (Jimenez-Reyes et al., 2017).

However, this improvement observed in the study of Jimenez-Reyes et al. (2017) was measured in the height of an athlete's squat jump, that was the same movement used for the force-velocity evaluation. The testing presents, therefore, great specificity for the performance in that movement. It seems even reasonable to assume that this test would have transfer to other kinds of vertical jumping. But what if we want to test the performance in a more specific movement?

The results and importance of force-velocity testing and profiling seem promising but its results are specific to each movement. When it comes to the upper limbs, the literature is more scarce but some studies have researched this relationship in both bench press throws (Rahmani et al., 2018; Sreckovic et al., 2015) and with medicine balls (Sreckovic et al., 2015).

Nevertheless, if our goal is to study the force-velocity capabilities in such a complex movement as the handball throw, a new method to do this assessment with more specific procedures is demanded. Regarding this approach, to our knowledge, there are almost no studies with such methodology. Tillaar & Ettema (2004) studied overarm throwing with different ball weights (0.2 to 0.8 kg) and found a linear relationship between force and velocity and no change in the global coordination patterns of throwing across the entire range of balls. However, even though they tested handball players, it is important to note that smaller balls were used (circumference 0.3m). Additionally, a preliminary study by Estriga et al. (2019) was performed with a similar methodology to the one proposed here. The authors computed an optimal ball weight with which the players would produce the most power and showed that, in that case, the players presented a velocity deficit, since they would produce more power with heavier balls.

This exploratory study aims to develop a new and more specific methodology that can evaluate the force-velocity relationship in overarm throwing of handball players.

3.3. Objective

The aim of the experimental study 1 is to develop a specific methodology to evaluate the force-velocity capabilities in overhead throwing, which involves designing and testing innovative measurement procedures.

The goal of this methodology is to be more specific and to reproduce the complex characteristics of handball throwing.

3.4. Methodology

3.4.1. Subjects

Nineteen adult male handball players (age= 21.74±2.96, body mass= 92.09 ± 12.10, stature= 1.86 ± 0.07) were tested. All of them were playing in the Portuguese first division.

The participants were previously informed about the purpose and objectives of the study and signed a declaration of informed consent. Furthermore, this study was approved by the ethical committee of the Faculty of Sports of the University of Porto. All recruited subjects had no shoulder pain at the time of the testing or any previous shoulder injury or pathology.

Table 1. Characterization of the subjects that participated in the data collections

Subject (ID)	Age	Weight (kg)	Height (m)
1	20	108.3	1.94
2	19	77.2	1.72
3	20	98.9	1.8
4	19	73.7	1.82
5	22	86.8	1.84
6	31	106	1.78
7	23	105.2	1.93
8	22	72	183
9	21	113	1.98

10	18	90.3	1.86
11	23	83.5	1.81
12	20	87.2	1.9
13	25	97.1	1.85
14	19	108	1.97
15	24	90	1.95
16	20	77.4	1.83
17	21	82	1.83
18	23	83	1.77
19	23	90	1.76
Average	**21.74±2.96**	**92.09±12.10**	**1.86±0.07**

3.4.2. Experimental Procedures

For the data collection, four handballs (size 3) with different weights were used: 433 kg, 546 kg, 607 kg and 747 kg. While the first ball has the official weight allowed (between 425 to 475 g), the other three were modified by hand, adding weight but assuring that this was well distributed throughout the ball.

Due to logistical reasons the tests were conducted in two different sessions and locations. In one session, fifteen players from the same team performed the tests during a training session, after 20 minutes of a standard warming up, with throwing tasks included. Because of time constraints, each subject did only two shooting attempts with the same ball, consisting in a total of 8 throws per each. In another session, four participants agreed to perform the testing in the Sport Faculty facilities, were there was no time limit for the testing. In this case, three shooting attempts were done. These subjects also performed a similar warming up protocol. In all situations, a set of four players were organized to perform the throws randomly with each of the four different balls, with one minute and thirty seconds of rest between attempts. The participants were asked to replicate a 7-meter throw (and thus, without lifting one of their feet) with their maximal shooting velocity.

Figure 12. The setup for the data collection with the 4 balls with different weights and the radar behind the goal

Maximal velocity was measured with a radar gun (Stalker Radar, Plano, TX, USA) with ± 0.028 m·s1, accuracy within a field of 10 degrees from the gun that was placed behind the goal.

Furthermore, it is important to refer that all the procedures were performed during the Covid-19 pandemic. For that reason, and because the pandemic delayed the data collections, the tests were performed during the pre-season, after the athletes were allowed to start training without restrictions (all the players were only training at home for 4 months). All the recommendations given by the health authorities were followed, with the researchers wearing masks at all time, and maintaining social distance.

3.4.3. Data Processing and Analysis

During each throwing execution a radar placed behind the goal was used measure the maximum throwing velocity. The ball's acceleration distance (when in the hand) would be estimated either by integration on the velocity (obtained with the radar) or directly from a video record.

So, for each execution one has the ball's mass (**m**), the throwing velocity (**v**) and the acceleration's length (**s**). Here, we have to mention that a standard acceleration's length of 0.5m was assumed for simplification.

From the energy/work equations one deduces the average force exerted by the player on the ball (F_{ave})

$$\frac{1}{2}mv^2 - 0 = F_{ave} \cdot s \qquad (1)$$

$$F_{ave} = \frac{mv^2}{2s} \qquad (2)$$

A power figure (**P**) was also computed as the product of the average force by the throwing velocity

$$P = F_{ave} \cdot v \qquad (3)$$

Although one might doubt the biomechanical significance of the average force and throwing power, these are the usual procedures described in the literature (Samozino et al., 2008; Samozino et al., 2012).

From the set of all throws, for each subject a quadratic regression was performed in the power-velocity space (linear in the force-velocity one). Again, this is just the *standard* procedure, not a physiological/biomechanical truth.

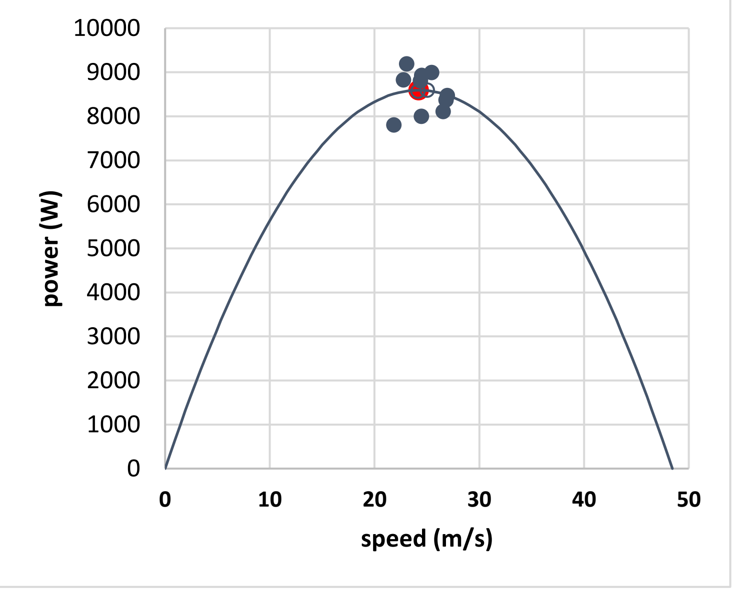


Figure 13. Power-velocity relationship obtained from a representative subject. The red symbol represents maxim computed power.

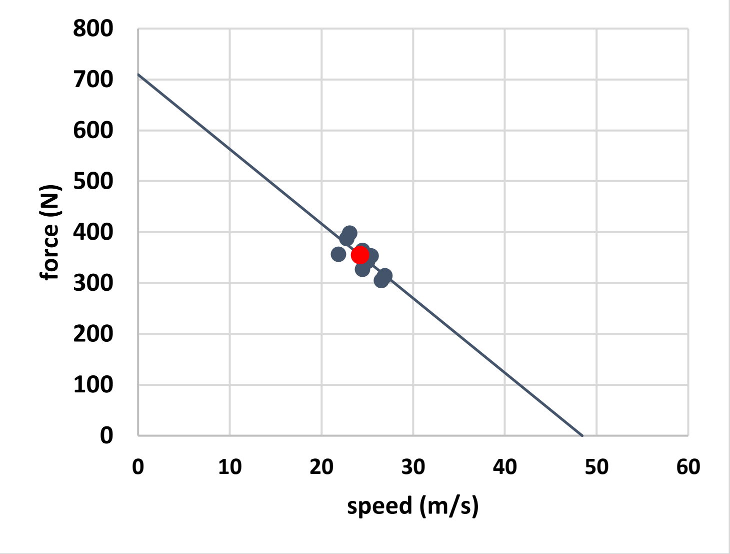


Figure 14. Force-velocity relationship obtained from a representative subject. The red symbol represents maxim computed power.

The apex of the parabolic regression originates the optimal mass, the one that elicits the maximum throwing power with the help of equations 2 and 3

$$P_{apex} = F_{apex} v_{apex} \Leftrightarrow P_{apex} = \frac{m_{opt} v_{apex}^2}{2 s_{apex}} v_{apex} \Leftrightarrow$$

$$m_{opt} = \frac{2 s_{apex} P_{apex}}{v_{apex}^3} \qquad (5)$$

The acceleration length for this (virtual) throw is obtained from another [linear] regression in the *mass-acceleration_length* space (so equation 5 still needs to be solved for that)

$$m_{opt} = \frac{2(a \cdot m_{opt} + b) P_{apex}}{v_{apex}^3} \Leftrightarrow$$

$$m_{opt} = \frac{\frac{2b \cdot P_{apex}}{v_{apex}^3}}{1 - \frac{2b \cdot P_{apex}}{v_{apex}^3}} \qquad (6)$$

Finally, one can compare this optimal ball mass with the official ball (see the example of the subject 18 in the figure 15).

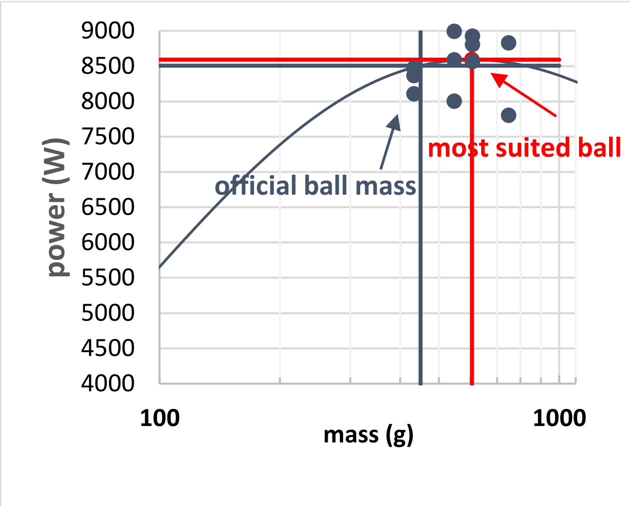


Figure 15. The red dot located in the peak of the power-velocity curve, represents a theoretical optimal ball that would maximize power output.

This comparison still needs reasoning over its significance. In the above example, the optimal ball's mass (605g) is significantly larger than the official ball's mass (450g) but the power gain (8590W *vs* 8500W) is well below the statistical uncertainty.

In conclusion this method, strongly based in the literature, has a few caveats: the physiological/biomechanical significance of some of its intermediate results (e.g. average force, power) and the need for a large set of measures to obtain statistically significant results.

3.5. Results

In the table 2 are presented the values of both maximal throwing velocity (best attempt) and the mean velocity of all attempts.

Table 2. Maximum and mean values of the throwing velocity (Km/h) with the different ball weights.

	Ball Weight (g)							
	433		547		607		747	
Subject (ID)	Máx.	Mean (±SD)	Máx.	Mean (±SD)	Máx.	Mean (±SD)	Máx.	Mean (±SD)
1	91.8	91.1±0.99	90.3	89.8±0.71	86.1	83.5±3.68	82.5	82±0.71
2	82.1	80.5±2.26	73.4	73.2±0.28	75	74.75±0.35	70.5	69.9±0.85
3	81.9	80.6±1.84	77.3	77.3±0.00	74	73.7±0.42	69.9	67.15±3.89
4	76.2	76±0.28	77.8	76.9±1.27	69.4	69.3±0.14	66.4	66±0.57
5	73.9	73.65±0.35	71.6	66.95±6.58	72.4	70.9±2.12	69.8	69.5±0.42
6	77.2	74.6±3.68	72.2	71.7±0.71	70.6	68.65±2.76	62.3	61±1.84
7	100	98.55±2.05	96.2	93.3±4.10	92.1	89.85±3.18	86.2	85.9±0.42
8	94.5	93.5±1.41	86.4	84.9±2.12	77.4	76.35±1.48	76.9	76.2±0.99
9	95.2	94.75±0.64	92.3	92.25±0.07	91.1	90.4±0.99	75.4	75.25±0.21
10	93.9	92.75±1.63	90	89.25±1.06	86.4	84.45±2.76	81.6	81.25±0.49
11	78.9	78.1±1.13	77.4	75.8±2.26	73.5	69.7±5.37	66.8	66.45±0.49
12	87.2	86.2±1.41	83.8	81.85±2.76	81.5	79.1±3.39	72.3	70.8±2.12
13	86.5	85.45±1.48	87.7	87.65±0.07	87.7	85.6±2.97	75.8	74.1±2.40
14	97.6	94.7±4.10	90.8	88.35±3.46	88.4	83.15±7.42	88.7	81.55±10.11
15	98.6	96.55±2.90	90.7	88.45±3.18	85.6	84.8±1.13	79.9	78.5±1.98
16	84.8	84.30±0.50	83	82.90±0.17	80.2	78.43±1.80	74.4	73.73±0.65
17	91.1	90.93±0.15	86	84.10±2.69	83.2	82.10±1.57	76.7	75.93±1.24
18	97	96.40±0.72	91.6	89.97±1.76	88.2	87.67±0.61	83.1	81.27±2.29
19	77.3	76.30±1.05	73.4	73.10±0.26	73.9	71.43±2.40	68.9	66.90±2.05
Total	**87.67±8.56**	**86.61±8.33**	**83.78±7.85**	**82.47±7.87**	**80.88±7.38**	**79.22±7.32**	**75.16±7.19**	**73.92±6.87**

As the aim of this study is to develop a new methodology for the individual evaluation of force-power-velocity capabilities in handball, individual analysis were carried for each athlete. During this analysis, we realized that the data of some of the subjects was statistically weak (low coefficient of determination, R^2) and, therefore, we focused the analysis on a more restrict group. In the figure 16, we show an example of one of the excluded subjects. As it is possible to observe, the optimal ball weight (peak of the power curve) appears outside the range of our data and, thus, to predict it, we would be performing extrapolation.

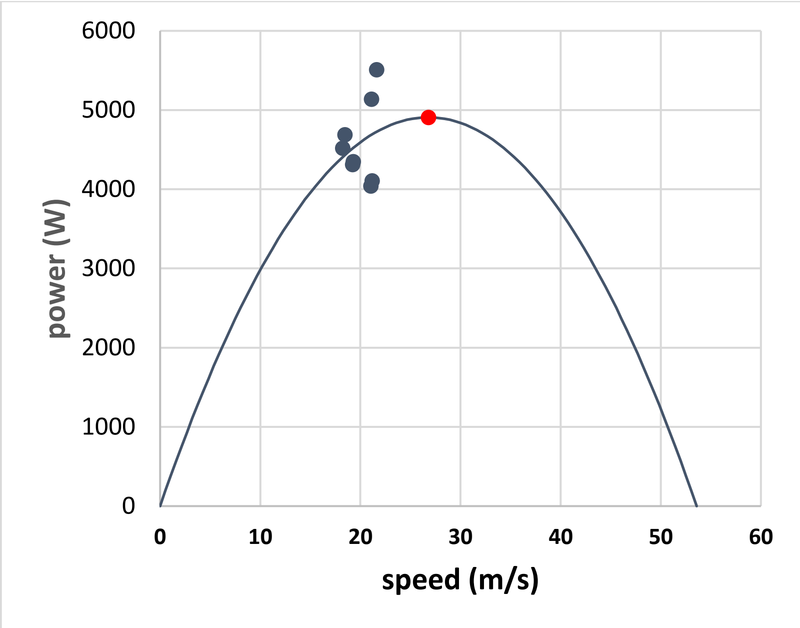


Figure 16. Example of one of the subjects that presented low R^2 (0.135) and a theoretical optimal ball weight outside the range of the data ()

For that reason, we selected a more restrict group of seven subjects with higher R^2 that are presented in the table 3, together with their throwing velocity, force and power with the official ball, in comparison with the same measures with the theoretical optimal ball weight (for power maximization).

Table 3. Throwing velocity, force and power with both the official ball and the theoretical optimal ball weight.

	Official ball				Optimal ball weight			
Subject (ID)	**Throw velocity** (m/s)	**$Force_{mean}$ (N)**	**P_{max} (W)**	**R^2, N**	**m_{opt_ball} (kg)**	**Throw velocity** (m/s)	**Force (N)**	**P_{max} (W)**
2	22.18	221.46	4912.87	0.45, 8	0.968	17.59	299.69	5272.09
7	27.42	338.33	9276.97	0.45, 8	0.825	22.73	426.37	9690.10
10	25.80	299.58	7729.80	0.61, 8	1.052	20.02	421.39	8434.57
16	23.75	253.80	6027.45	0.56, 12	0.694	18.91	341.20	6450.69
17	25.14	280.47	7050.12	0.50, 12	0.444	25.02	281.75	7049.98

18	26.64	319.32	8506.19	0.65, 12	0.605	24.22	354.78	8592.01
19	21.46	207.23	4447.11	0.42, 12	0.755	18.25	251.50	4589.27

In the figure 17, a scatterplot of all the attempts performed by the seven athletes mentioned before and its force-velocity relationship is represented. Additionally, a force-velocity relationship is drawn for the mean data with each one of the ball weights.

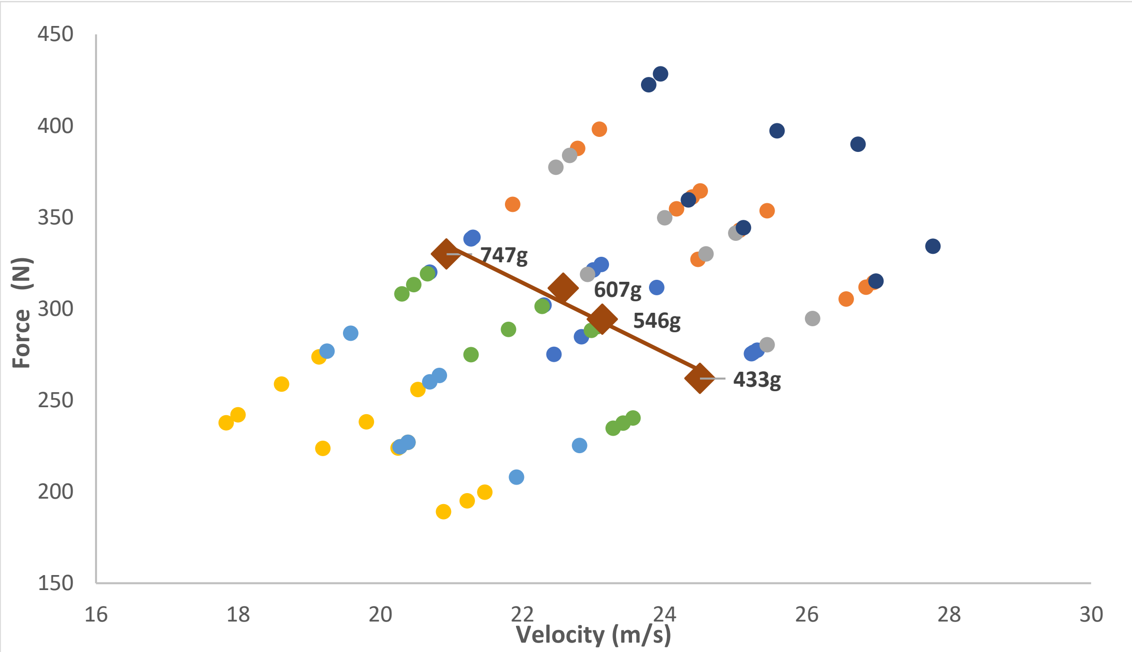


Figure 17. Relation between force and velocity for each throwing attempt. Each colour represents a different subject. The lozenges represent the mean data for each ball weight.

3.6. Discussion

The main objective of this study was to develop a methodology that could evaluate the force-velocity capabilities in handball throwing. The literature is not extensive when it comes to assessing the force-velocity characteristics in multi-joint movements and it barely exists regarding these assessments in a movement so specific as handball throwing. Therefore, the literature we have available to discuss the results of this study is scarce.

Our data revealed a linear relationship between force and velocity in handball throwing. These findings converge with the already mentioned study of Tillaar & Ettema (2004) that is the only one that, to our knowledge, studied force-velocity characteristics in overarm throwing with handball players. Furthermore, the literature also points that, in other multi-joint movements, this linearity of the F-v relationship is also observed (Cuk et al., 2014; Samozino et al., 2012; Sreckovic et al., 2015). This linearity means that, when velocity increases, the force produced decreases. However, and as discussed in the literature review, one must be careful when interpreting these results, as the mechanisms that lead to this linearity are not fully understood. Despite the importance of knowing the seminal study of Hill (1938) in a muscle fibre, we cannot interpret this results as being only determined by muscle properties. In multi-joint movements, this force-velocity relationship can be influenced by several factors as mixed-fibre composition, architectural characteristics, anatomical joint configuration or levels of neural activation. If for movements like the bench press or the squat, this relationship is already complex, this assessment in movements like handball throwing brings new problems: the complexity of the movement, muscle synergies and coordination (technique).

Despite all the complexity, examination of the force-velocity relationship in a movement like handball throwing, quantifies the ability of the entire neuromuscular system to function under different loading conditions and, thus, can allow a better understanding of the strengths and weaknesses of each individual.

Our study outcomes revealed that the developed method appears to help in determining each player’s profile (such as speed or force limited) in standing overarm throw and, therefore, might be useful to optimize individual training. In figure 18 we can observe that, for a specific subject, the theoretical most suited ball (ball weight with which the athlete would produce more power) is a lot heavier (605g) than the official ball (425-475g). These results indicate that this athlete has a more force-oriented profile and might have a speed deficit. These observations are in line with the ideas of Morin & Samozino (2015) that consider that an evaluation of individual force-velocity (in our study, the consequent power-velocity) relationships can help identifying imbalances and optimize strength training, according to individual necessities. Furthermore, to strengthen this perspective, Jimenez-Reyes et al. (2017) showed that training addressing own imbalances and deficits (studied with force-velocity assessments in squat jump) is more effective than training following “one-size-fits-all” programs. If the subject on figure 18 wants to improve is throwing velocity, then the focus should be on minimizing this speed deficit. This doesn’t mean that strength training with heavy loads will be detrimental, it simply means that, specifically for throwing (we are not discussing all the other aspects of the game), training with higher velocities should be optimal for him. However, force-velocity (or power-velocity) profiling provides information about what specific muscle outputs should be developed but not on how this should be done (Morin & Samozino, 2015). The methods with which the subject on the figure could train to improve his throwing velocity are yet to be studied and, if the methods used to work on strength deficits are more clear, the means to work on speed deficits are still to be understood, especially on a specific movement as handball throwing.

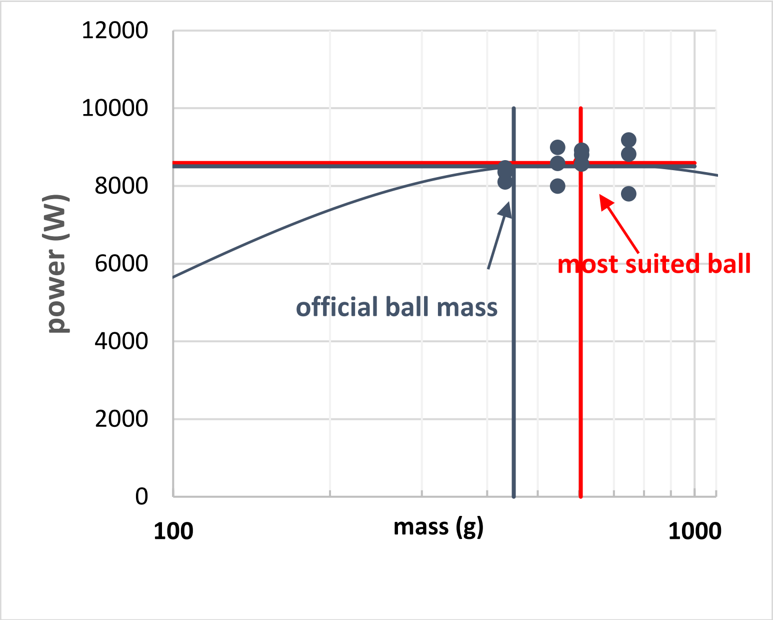


Figure 18.Example of a force-orientated profile

Some research has been testing different methods of training and its influence on throwing velocity. Hermassi et al. (2011) observed an increase in throwing ball velocity after 8 weeks of heavy resistance training. Improvements were also found with programs including 8 weeks of plyometric training (Chelly et al., 2014), 8 weeks of training with medicine ball throwing (3 kg) (Hermassi et al., 2015) and 8 weeks of additional elastic training performed twice a week (Aloui et al., 2019). Another method that appears to be useful is Olympic weightlifting, as Hermassi et al. (2019) found a high correlation with throwing velocity (especially for the clean and jerk).

Summing up, several training methods seem to be useful to increase throwing velocity, using either heavy loads or light loads. Hermassi et al. (2011) even concludes that heavy load strength training can be performed without adverse effects on speed of movement. The problem is that, even though these studies are useful to understand the effectiveness of these methods, most of them compare the experimental groups to control groups that have less workload. Therefore, from all those conclusions, we still don't know what the optimal method is. Bragazzi et al. (2020) in a systematic review about these methods, concludes that the best way to improve throwing velocity is to combine resistance training with heavy loads and more specific training with lighter loads, a mixed-methods approach. This takes us back to the discussion presented in the chapter 2.4.

Given that training with both heavy and light loads has its benefits, this mixed approach does appear to be the most effective to obtain all-round improvements in the force-velocity curve and to maximize power outputs. However, even though this may be true for the average of subjects, which explains the positive outcomes in all the studies mentioned before, in sports we search for the improvement of an individual and not of an average. We can observe from our results that two subjects (figure 18 and 19) can have different profiles. We then hypothesize that the training that would be optimal for the average, would have different outcomes if applied to these two subjects. This profiling could then be a tool to identify the optimal training for each individual, according to its necessities. Further studies are needed to understand the impact of different training methodologies on this force-power-velocity relationship.

It is important to notice, however, that this evaluation of the imbalances and deficits is only a small part of what strength training is. From our understanding, the lack of detected imbalances doesn't mean that there is no need to work on the force or speed capabilities. If we observe figure 19, we can verify that the theoretical optimal ball for this subject has the weight of an official ball (444g). It means simply that this athlete doesn't have imbalances between force and velocity capabilities. It probably means that he should work those capabilities on a balanced way (Jimenez-Reyes et al., 2017).

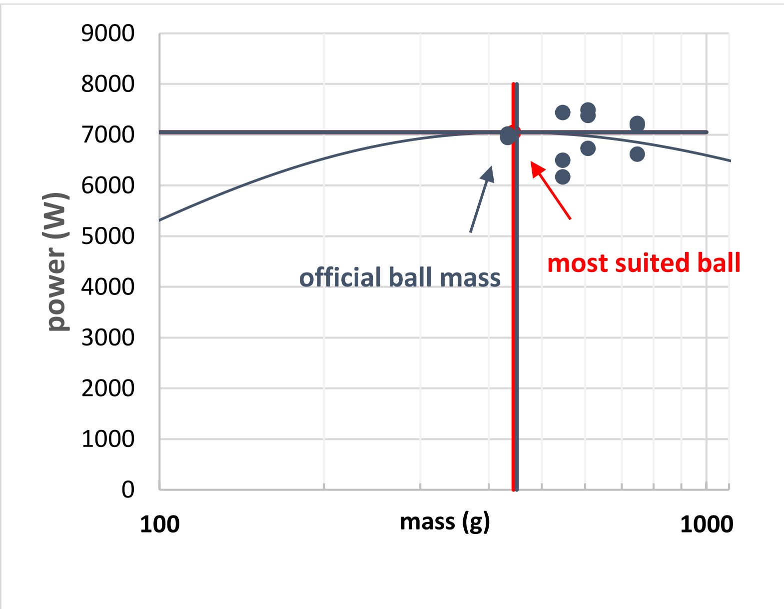


Figure 19. Example of a balanced profile.

One should be aware that, even though these individual assessments appear to offer some valuable insights about the athlete's needs, the methodology used in this study still has several limitations, some of them already mentioned in the data processing and analysis chapter.

First of all, acceleration was not measured directly. Due to methodological difficulties and time constraints, it was not possible to measure acceleration as initially defined. The direct measure of acceleration would allow to calculate force with a more real approach and, therefore, have more accurate force-velocity and power-velocity relationships.

Another aspect that should be assessed in order to have more control over the variables of the throw is the throwing angle. As we know, handball throwing technique is not exactly the same between athletes and even between throws. An approach similar to the one used by Tillaar & Ettema (2004), that used high velocity cameras and reflective markers to record the movement could be one way to reduce the effect of the variation in throwing technique and to know ball's acceleration distance (until the point of ball release).

Moreover, the time constraints, together with the fact that this is an innovative approach, didn't allow us to test the methodology using a wider range of ball weights and a greater number of throws with each ball. In the figure 16, we could observe that the theoretical ball weight was outside the range of data collected. This could be solved by both increasing the range of ball weights or increasing the number of throws to reduce the learning effect. Increasing the range of ball weights is easy if we want heavier balls but hard if we need lighter balls (as we can add weight to official balls, but not remove it). Unlike Tillaar & Ettema (2004), we only used official ball sizes to eliminate a possible effect of the ball size on throwing velocity. However, the only way to have lighter balls seems to be to use smaller ones (size 1 and 2).

3.7. Conclusions

We have studied the ball's average throwing force *vs* the maximum ball velocity and encountered a linear force-velocity relation, similarly to other experimental evidences for multi-joint movements.

Our findings showed that the majority of the evaluated players would produce higher standing-throw power if the ball was heavier than the official size 3, meaning that they have a speed deficit and a more force-oriented profile. Therefore, they need to improve speed more than they need to improve maximum strength. This type of information will help coaches to diagnose each player needs and, therefore, might be a useful tool for individual profiling and for optimization of training. As a coach, this information leads to the need to have a better understanding of how traditional strength training affects players' throwing velocity and other ballistic movements, and how to address the challenge of training handball players on the high-velocity portion of the F-v curve.

The developed apparatus and methodology appear to be relatively simple to use and ecologically valid to assess force-velocity and power-velocity capabilities in handball throwing, but still need to be improved and tested with a larger sample and a wider range of balls' weight. This was an exploratory study and the methodology still has some faults. The assessment of acceleration, velocity and joint angles can further improve it and make it more reliable.

4. Force-velocity Relationship in Bench Press Throw and its Implications for Handball Players

4.1. Abstract

Bench press is one of the gold standards in strength training for handball players. It is mainly used for the training with heavy loads and the increase of muscle mass and maximal strength.

Additionally, when it comes to the assessment of the force-velocity relationship in multi-joint movements in the upper limbs, bench press seems to be the most researched movement (García Ramos et al., 2016; Rahmani et al., 2018; Sreckovic et al., 2015). However, even though it is the one that research has been focusing on, the method is still not well-founded and validated.

As it is standard for both training and researching, we developed an exploratory study to better understand the information it can provide and the impact it can have on handball players. Four Portuguese first division handball players performed bench press with 40, 60, 70, 80 and 90% of their RM. Each participant were instructed to perform three attempts for every load, but in the case of high loads, some subjects only performed two repetitions because of fatigue issues. The loads were chosen in a randomized order. A minimum of 30 seconds of rest between repetitions was used and 3-4 minutes between set/trials with different loads. Additionally, the four subjects performed three handball throws with a set of four ball with different weights.

Even though, add to the evidence that loaded bench press throws can be used to study upper limbs force-velocity capabilities, there were some findings that are important to further research. It appears that, for heavy loads, there are some "curls" in the F-v relationship that change its shape. This fact has not been reported in other studies, and further research is needed to understand the exact causes and its interpretation for effective individualized training based on power-force-velocity profile.

Furthermore, the comparison of the slopes between the force-velocity curves with bench press throws and with overarm handball throwing exposed the complexity of the problematic and open up future questions for research.

4.2. Introduction

As discussed in the main introduction, the bench press throw was chosen for this exploratory study for two reasons: from the already tested standard procedures is the one that presents more similarities with handball throwing; bench press is routinely used in handball training.

When it comes to the study of the lower limbs, the literature is more extensive and the findings regarding the shape of the force-velocity curve have been consistent (Jaric, 2015). Despite the inferior number of studies, the investigations in ballistic movements in the upper limbs, and more concretely in the bench press throw, also point to the linearity of the force-velocity curve (García Ramos et al., 2016; Sreckovic et al., 2015). Additionally, both the studies of García Ramos et al. (2016) and Sreckovic et al. (2015) found that the reliability is higher in the F0 and P0 than in V0, fact that was also verified in previous studies. Both groups of authors also add that F0 strongly correlates to directly measured maximal strength (1RM) and that the evaluation of the force-velocity relationship in the bench press throw is useful to assess the upper body maximal capabilities to generate force, velocity and power.

The intent of this exploratory and cross-sectional study is to acquire new insight on the rationality of the use of loaded bench press throws to evaluate the force-velocity capabilities in handball players. Moreover, this study aims to address the provided information from the two different methods applied to evaluate ballistic performance in throwing: bench press throw and overarm throwing in different loading conditions, developed in the previous study.

4.3. Objective

Experimental study 2 aims to explore information provided by the assessment of standard bench press throw performance through different loading magnitudes (40%,60%,70%,80%,90%), namely to determine which variables might be more informative about individual power capabilities and F-v relationships.

4.4. Methodology

4.4.1. Subjects

As this is an exploratory study, a small sample size of adult male handball players was recruited. Therefore, a set of four subjects participated in this experiment. All of them were playing in the Portuguese first division and had, on average, 13 (± 2) years of playing experience.

The participants were previously informed about the purpose and objectives of the study and signed a declaration of informed consent. Furthermore, this research was approved by the ethical committee of the Faculty of Sports of the University of Porto. All recruited subjects had no shoulder pain at the time of the testing or any previous shoulder injury or pathology.

Table 4. Characterization of the sample

Subject (ID)	Age (years)	Weight (kg)	Height (m)
#1	20	77.4	1.83
#2	21	82	1.83
#3	23	83	1.77
#4	23	90	1.76
Average (± SD)	**21.74(±2.96)**	**92.09(±12.10)**	**1.86(±0.07)**

4.4.2. Experimental Procedures

The participants performed a standard 20 minutes warm up that included handball throwing. First, the subjects completed an evaluation of the F-v relationship in overarm throwing. The methodology used in the previous study (Force-velocity Relationship in Overarm Throwing) was replicated and, thus, all the procedures can be found in the chapter 4.3.

The bench press throws were performed with a vertical guided barbell. Each participant completed a set of few bench press throws with the Smith machine unloaded (10kg) for a brief familiarization with the movement. The players were instructed to execute the bench throw as fast as possible while maintaining shoulders at ±90% of abduction to ensure consistence in movement patterns. The feet had to be in contact with the floor with the pelvis contacting the bench.

To determine the incremental loads used in the force-velocity assessment, a previous assessment of the 1RM was employed. To make it more practical and less time consuming, the participants were asked for their estimated RM and then performed an attempt with that same value. From the number of repetitions achieved with the heavy load (maximum of 4 or they would need to rest 5 minutes before attempting with a new load), the RM value was estimated according to Brzycki (1993).

The bench press throws were then performed with 40, 60, 70, 80 and 90% of their RM. Each participant were instructed to perform three attempts for every load, but in the case of high loads, some subjects only performed two repetitions because of fatigue issues. The loads were chosen in a randomized order. A minimum of 30 seconds of rest between repetitions was used and 3-4 minutes between set/trials with different loads. Two spotters were positioned at both sides of the machine to ensure safely to the players. All the testing procedures were controlled and supervised by a highly experienced researcher on strength evaluation and training. In each execution the player started by holding he bar with the arms fully extended. From that position, he initiated a downwards movement, until the bar was positioned ±1cm above his chest, parallel to the nipples, before initiating the upwards move (i.e. concentric phase) as fast as possible. Only the data about the concentric phase was recorded.

Figure 20. Setup for the data collection.

Furthermore, it is important to refer that all the procedures were performed during the Covid-19 pandemic. For that reason, and because the pandemic delayed the data collections, the tests were performed during the third week of the pre-season. It is import to mention that in the previous four months the subjects were only allowed to train at home. All the recommendations given by the national and local health authorities were followed, with the researchers wearing masks at all time, and maintaining social distance.

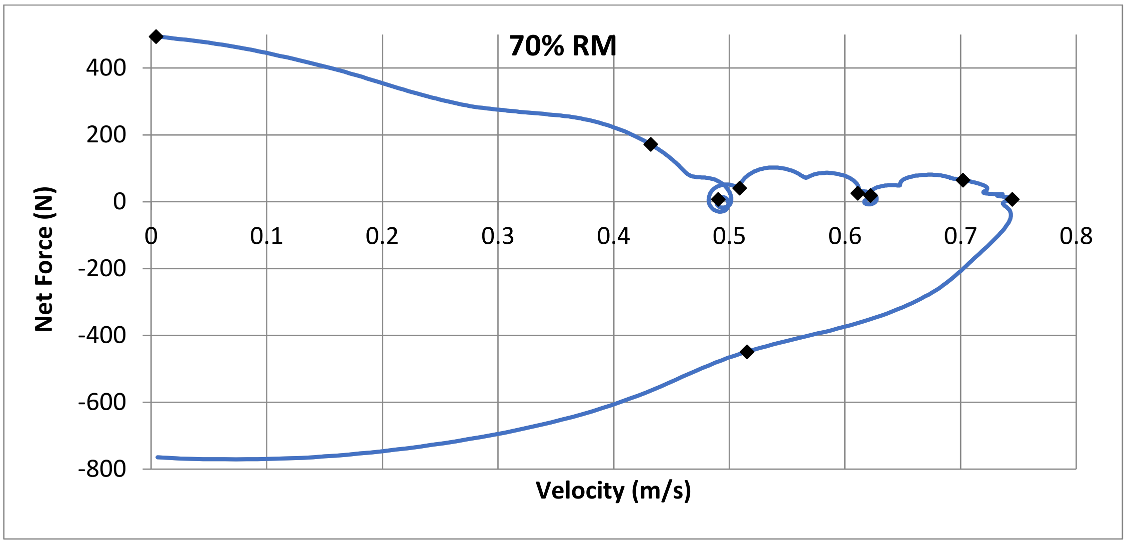
4.4.3. Data Processing and Analysis

Velocity was measured with a linear velocity encoder (T-Force Dynamic Measurement System, Ergotech, Múrcia, Spain) according to the manufacturer's specifications. Data were sampled at a rate of 1000Hz. Bar velocity was recorded with an error of <0.25%. The validity and reliability of the T-Force system was reported by Sánchez-Medina & González-Badillo (2011).

The manufacturer's software provided an excel sheet with the date regarding the concentric phase of the lifting: "Time (ms)", "Space (m/s)", Velocity (m/s), "Force (N)", "Power (W)", and RFD (N/s). The P output was calculated as a product of F and V. The net Force ($\mathbf{F}_{net}$; N) was computed by the product of load (mass) and acceleration. Note that only the date from the upward phase was recorded. Since there was technical debuts about the onset of data recording in the concentric phase, the throw distance was not considered for analysis, and therefore this is a limitation. The F-V and P-V relationships were estimated from individual F, V, and P obtained under five loading magnitudes, separately for their maximum and mean values.

In data processing, it is common to apply filters to eliminate "noise" or certain unwanted date features. In the case of this type of date, we might speculate that the authors are attempting to get more smoothing F-v curve as it is known from the Hill's curve for a muscle fibre. However, we decided to know more about our date and to understand what filters (e.g., 5 Hz, 10 Hz, 15Hz) do and when to use it.

Consequently, we did a preliminary visual inspection of the obtained curves with the raw and filtered data (a fourth-order low-pass Butterworth filter with a cut-off frequency of 5Hz and 200 samples/s), as it is illustrated in the figure 22.



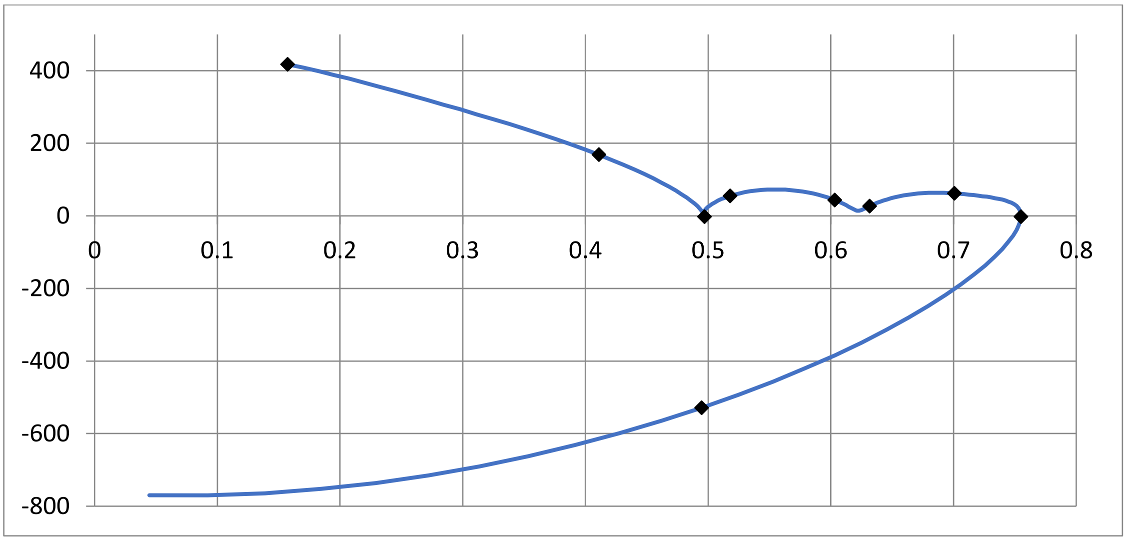


Figure 21. Raw data (top graphic) and filtered data (bottom graphic) for subject 1. The black dots represent an interval time of 100ms. 70% of the RM corresponds to 76kg for this subject.

In the example above with 70% of an RM we can observe how the applied filter shapes the “curls” and produces an aliasing effect. The black dots in the figures are placed with an interval of 100ms for better reading and interpretation of each graph characteristics. For instance, in the raw data graph, we can observe small “curls” that change the shape and dynamic of this relationship over time. We will come to the meaning of this “curls” effect latter on. We also compared the impact of using a sample rate of 1000 Hz (García Ramos et al., 2016) with 200Hz (Sreckovic et al., 2015) in the main outcomes for each selected variable, and the results didn´t differ much, as can be observe in the next table.

Table 5. Comparison of maximal values of power, velocity and force, between raw and filtered data. (#3)

	Raw			Filtered		
Load (%RM)	**Power (W)**	**F (N)**	**V (m/s)**	**Power (W)**	**F (N)**	**V (m/s)**
44%	599.58	509.96	1.45	591.66	491.43	1.45
44%	571.02	472.59	1.42	562.63	463.76	1.40
58%	614.70	869.75	1.18	599.91	809.83	1.18
58%	585.60	717.13	1.15	582.84	698.72	1.15
58%	542.56	752.49	1.06	533.94	725.03	1.06
70%	508.09	734.37	0.86	512.52	723.30	0.85
70%	582.39	682.30	0.95	586.02	683.30	0.95
75%	515.92	814.39	0.82	524.43	776.84	0.82
75%	485.70	740.06	0.77	492.46	733.89	0.78
75%	470.81	716.19	0.75	473.31	713.25	0.75
88%	460.76	848.70	0.62	437.85	816.48	0.61
88%	384.05	802.75	0.52	369.84	773.56	0.52

4.5. Results

In the table 5 we describe the estimated 1 RM for each subject and the used loads for each percentage of the RM. It is important to notice that, the loads used are not exactly the described percentage but are the closer load possible with the weight plates available. In table 6 the real % of RM used is presented.

Table 6. Estimated RM and used loads.

	Load used (Kg)					
Subject (ID)	1 RM	90%	80%	70%	60%	40%
#1	109	95	85	76	66	45
#2	100	90	80	70	60	40
#3	79.8	70	60	56	46	35
#4	73.5	66	56	50	45	30

In the table 7 are presented the mains results obtained from the raw data of the points of maximal power output (**P**max) for each percentage of the RM and the corresponding velocity, acceleration and force at that same point. The values of maximal force, maximal velocity outputs and propulsive force (average force from the start of the concentric phase until the acceleration of the bar is lower than gravity) are also presented in the table (right side). In the attachments, a more complete data for each set is presented.

Table 7. Main results referring to the values at the point of maximal power output and the corresponding measured values of velocity, acceleration and force, as well as the maximum values of force (Fmax), velocity (Vmax) and propulsive force (Fprop).

Subject (ID)	**Load (%RM)**	**Velocity (m/s)**	**Aceleration (m/s^2)**	**Force (N)**	**P_{max} (W)**	**F_{max}**	**V_{max}**	**F_{prop}**
#1	41%	1.51	3.20	585.53	884.12	936.83	1.61	648.41
	61%	0.90	2.08	785.06	704.39	1005.64	0.98	779.40
	70%	0.85	1.38	850.76	726.22	1218.56	0.90	858.76
	78%	0.53	0.97	916.46	482.13	1176.46	0.54	875.33
	87%	0.72	1.05	1031.64	742.40	1377.41	0.74	1004.71
#2	40%	1.63	3.33	525.59	857.70	994.91	1.75	579.50
	60%	1.11	2.36	730.28	808.15	938.64	1.18	726.74
	70%	1.06	1.87	700.76	739.85	1171.84	1.02	797.25
	80%	0.80	1.33	890.95	713.15	1598.97	0.82	860.40
	90%	0.57	1.29	998.99	573.78	1051.07	0.59	952.16

#3	44%	1.37	2.67	436.90	599.58	509.96	1.45	452.36
	58%	1.13	2.01	543.58	614.70	869.75	1.18	556.46
	70%	0.89	1.85	652.72	582.39	682.30	0.95	610.99
	75%	0.80	0.99	648.01	515.92	814.39	0.82	649.07
	88%	0.60	1.14	766.50	460.76	848.70	0.62	712.86
#4	41%	1.60	3.24	391.50	625.83	599.27	1.69	433.09
	61%	1.16	2.37	547.97	636.08	685.27	1.22	537.83
	68%	1.00	2.56	618.66	615.59	643.45	1.06	566.96
	76%	0.92	1.75	647.41	594.86	785.29	0.95	612.43
	90%	0.82	1.50	746.50	613.74	869.27	0.84	719.53

4.6. Discussion

The current work is about the problematic of how to evaluate the force-velocity profile in handball throwing. As there is not a well-founded and validated method, our purpose is to explore the information from the bench press throw and then to compare it with the methodology developed in the previous chapter

The bench press is one of the most used strength training exercises by handball players. Therefore, one of the main reasons that led us to research on this specific matter is our empirical knowledge as player and coach that handball players train mostly with heavy loads and, specifically on the bench press. Hence, its traditional version is presumably used more often than the ballistic (with throw) version. When this is the case, the priority is the development of muscle mass and maximal strength, focusing more on the structural aspects (increase of CSA) and less on neural factors such as firing frequency and, so, having less impact on the rate of force development. The training solely with heavy loads/slow velocities doesn’t allow the enhancing of firing rates that is most optimized through the use of ballistic movements (Van Cutsem et al., 1998). Moreover, what frequently happens is that the focus on hypertrophy leads to decreases in relative strength and in performance in ballistic movements.

Assuming that the strength training design for each player should be based on his/her profile and game demands it seems essential to make an appropriate diagnosis. Therefore, one of the main challenges has been to find a method that could provide valid and reliable information about a player’s power-force-velocity profile.

One of the discussions in the literature is about the regression that best fits the force-velocity relationship (Alcazar et al., 2019). However, our results, just like the results from Sreckovic et al. (2015), show that the linear and the second order polynomial regressions overlap (see figure 22) and, therefore, this is not a matter that needs further discussion.

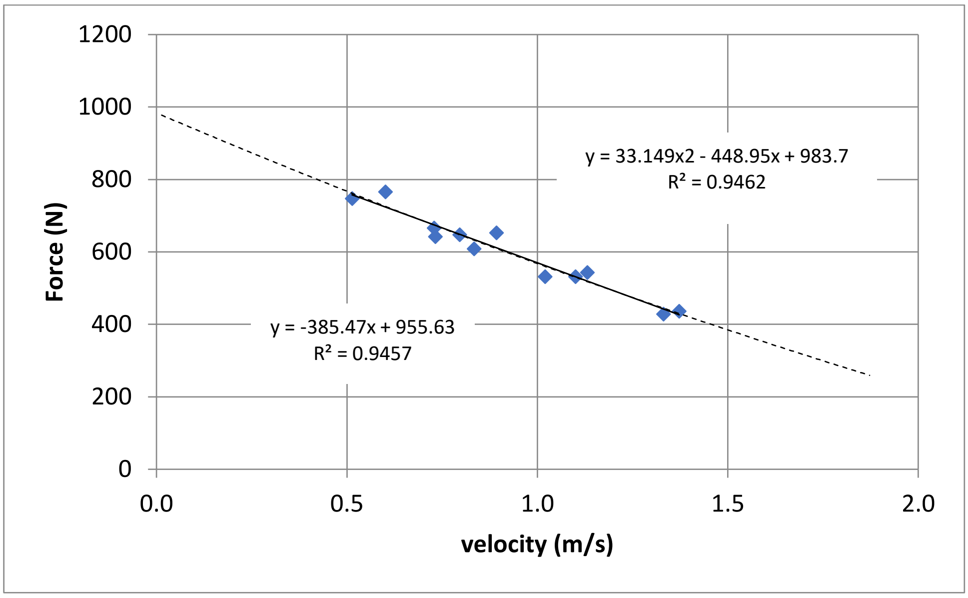


Figure 22. Linear (solid line) and second order polynomial (dashed line) regressions for subject 3.

In the figure 23 we can observe, as mentioned before, that the pattern of the force-velocity with heavy loads is different than the one with lighter loads, even when the player was able to effectively throw the bar with both loads. In the attempts with heavy loads we can see some "curls" that revealed a quite different curvature pattern and that were not addressed in previous studies while performing multi-joint exercises for upper (bench press) or lower body (leg press) (Cuk et al., 2014; García Ramos et al., 2016; Rahmani et al., 2018; Sreckovic et al., 2015). To our best knowledge, these finding seem to have be ignored by the literature. The lack to this issue is likely due to the data cleaning and reduction used in most of the studies (as already showed). However, from a physiological and biomechanical perspective this phenomenon makes sense, is expectable, and can be relevant to understand the characteristics of the force-velocity relationship with heavy loads and to make decisions about training. The knowledge of the mechanical and physiological aspects underlying muscle force production, at individual muscle fibres and motor units (e.g. recruitment, firing frequency) and in multi-joint movements (e.g. anatomical joint configuration, intermuscular coordination) can provide strong explanations for our results.

It is also important to mention that, even though our data analysis was done for each individual, the four of them presented a similar pattern with heavier loads. This "curls" start to appear when using 70% of one RM, but they become larger and clearer with the increase of load.

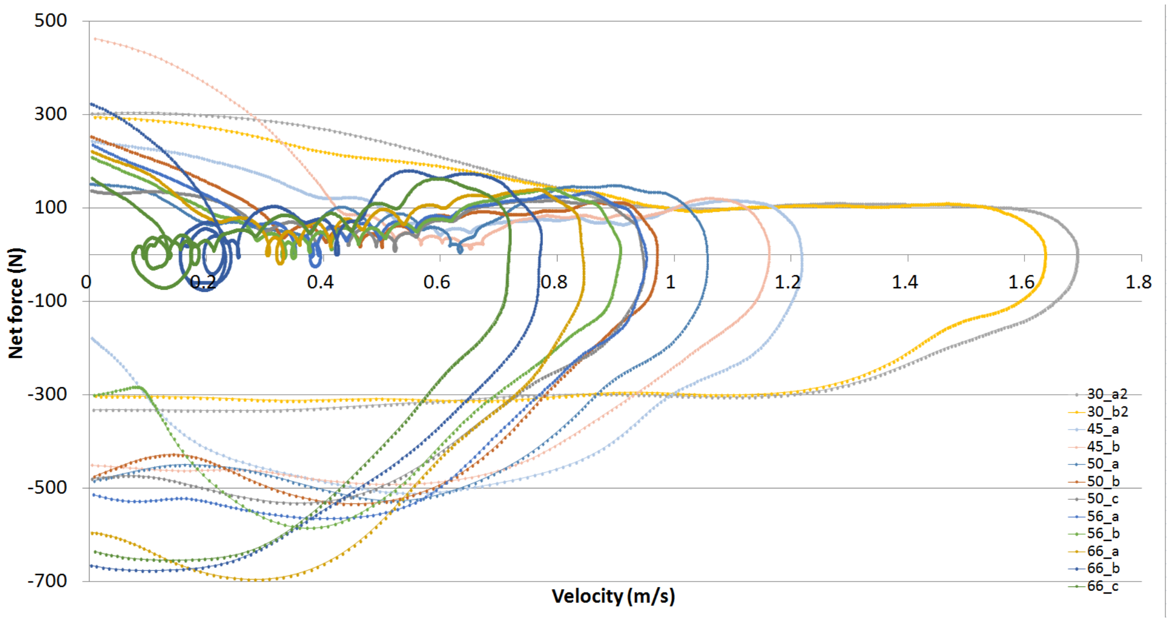


Figure 23. Example of force-velocity relationships with different loads for one subject (#4).

However, the reason for these “curls” to occur in the attempts with heavy loads needs further studying. The different angles, movement velocity and the changes in the force production needed at each one of them due to both to changes in moment arm and in muscle length may have an influence on this force-velocity relationship (MacIntosh & Holash, 2000). The fibre fatigue and the consequent need to recruit more fibres might have also an influence in the pattern of this force-velocity relationship as we know that, when lifting heavy loads, high threshold motor units that innervate type II muscle fibres are recruited after the lower threshold motor units are fatigued (Henneman et al., 1965). Even though, in ballistic movements, this MU’s are also recruited due to the lowering of thresholds, the differences in the process of recruitment may help explain the different patterns.

García Ramos et al. (2018) observed that, when assessing upper-body ballistic performance, there is a higher reliability or reproducibility when measuring velocity with lighter loads. The problem that practice pose us is that most of strength training programs in handball prioritize heavy loaded bench press and, therefore, it is important to understand the characteristics and implications of it. What these results show us is that the force-velocity pattern of bench press with heavy loads is different than the ballistic movements used in handball. It doesn’t mean that train with heavy loads does not have a space in handball training, but its transference for ballistic movements, like handball throwing, are questionable. In figure 24 we can look closer at the shape of the force-velocity relationship for three different attempts with the same load (80kg-80%RM) for subject 2. The first (green line) and second (blue line) attempts had similar velocities (0.83 and 0.82 respectively). However, if we look closer at the graphic, we can observe that they present different patterns. The second attempt clearly shows a larger curl, but somehow, they end up with almost the same maximal velocity. It seems that it shows an appearance of fatigue that was compensated by other factors. If we observe the third attempt (red line), however, we clearly see a bigger curl that can represent fibre fatigue and, in this case, the maximal velocity was lower (0.74 ms).

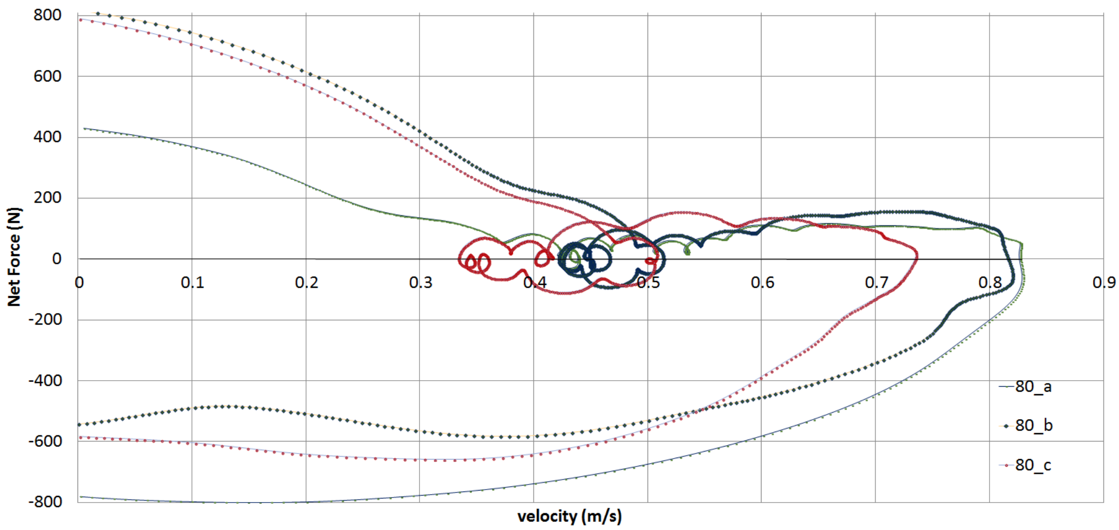


Figure 24. Force-velocity relationship for three different attempts with same load (80kg-80%RM) for subject 2

Additionally, and even though this just a rough comparison, if we observe figure 24, we can see the differences between the force-velocity relationship between handball throwing (left panel) and bench press throw (right panel). For the same subject, we realize that there are big differences in their slope. We can hypothesize that, even though bench press is one of the most used exercises, questions arise about its transfer to improve handball throwing performance. This reinforces the importance of having specific force-velocity testing for that movement and that, standard procedures with strength training exercises like the bench press are not enough to assess the force-velocity capabilities of a player in a specific and complex movement like handball throwing.

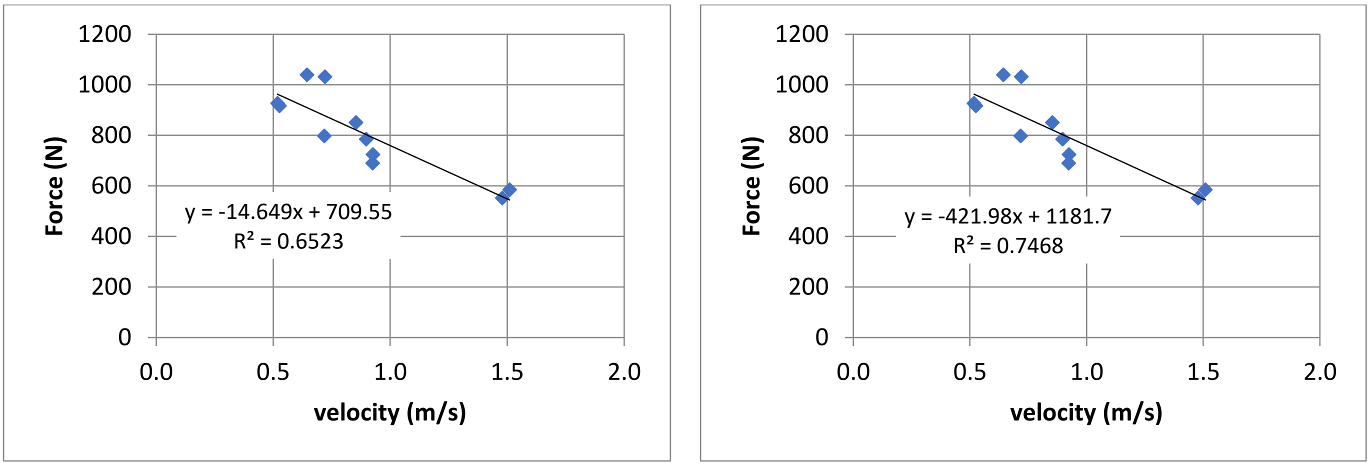


Figure 25. Force-velocity relationship in overarm throwing (left panel) and in bench press throw (right panel) for a representative subject (1)

This big differences in the slope are relevant, not only for the example showed, but for the four subjects tested. This reinforces the idea that testing using a more ecological method is needed to understand the real needs of each player.

Table 8. Differences in the slopes of the F-v relationships in handball throwing and in the bench press throw.

	Slope	
Subject	Handball throwing	Bench press throw
#1	-14.65	-421.9
#2	-13.78	-422.76
#3	-18.05	-385.47
#4	-11.16	-421.9

4.7. Conclusions

Our findings add to the evidence that the muscle mechanical properties could be studied through loaded bench press throws that provide linear F–v and parabolic P–v relationships.

However, our research also showed that, for heavy loads, there are some “curls” in the F-v relationship that change its shape. This fact has not been reported in other studies, and further research is needed to understand the exact causes and its interpretation for effective individualized training based on power-force-velocity profile. Our preliminary findings raises some questions about the validity of heavy loads both in research and in training.

Furthermore, the comparison of the slopes between the force-velocity curves with bench press throws and with overarm handball throwing exposed the complexity of the problematic and open up future questions for research. Although bench press throws may be useful to assess force-velocity capabilities of the upper limbs, it seems that it doesn’t really represent what happens in such a complex movement as handball throwing. This reinforces the importance of the specific and ecological methodology developed in the previous study.

5. Conclusions and recommendations for future research

Despite the limitations in the developed methodology and the need for further improvements, it seems that it is possible to assess the force-velocity capabilities in handball throwing with a relatively simple and ecological method. This allow us to better understand players' individual needs in this specific and functional movement. Additionally, we've exploited the F-v assessment using a standard resistance strength exercise (bench press throw) and analysed its limitations as an indicator and tool for the improvement of speed throwing velocity in handball.

Even though the bench press exercise does not resemble the movement pattern of a handball throw, the obtained linear F-v relationship should be further investigated as a tool to understand player's deficits and needs.

Our finding reveals that for each load (> 70% of RM) in the bench press exercise there is a very different and complex curve shape, so it seems very problematic to simplify it to a single point, as usually done. Therefore, more studies are needed, with bigger samples sizes and with more light loads to better understand how they correlate with each other.

It is important to mention that this was an exploratory study to develop and understand the limitations of the methods used. As such, both in the first and second study, we only performed the test in one moment. In the future, a second moment of testing should be performed a few days after the first. This retesting would be useful to measure the reliability of the data obtained.

If further developed, these methods allow the assessment of individual force-velocity profiles, which enables researchers and coaches to program training and understand its effect in the force-velocity capabilities of the athlete. The idea that was here developed that training according to individual profile is optimal to improve performance, and that was already tested for the lower limbs, can then be tested for handball throwing specifically. Furthermore, training according to individual profiling can help us understand, not only the final effect of each training method on throwing velocity, but also the optimal methods for training either force or velocity capabilities.

Research on this problematic can also help to set profiles for each playing role in the game and understand if there is a tendency for any position to have a specific profile as consequence of accumulated years of training load or/and a selection process. As an example, the line players might have force-oriented profiles due to their specific need to be robust.

Furthermore, handball specific force-velocity profiling can help to know more about the impact current strength training practices might have on handball performance and be essential to better understand developmental needs for youth players with different profiles in a long term basis.

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7. Attachments

Table 9. All data colected in the study 1

	Ball Weight (g)																			
	433					546					607					747				
Subject (ID)	Throwing velocity			Mean	SD	Throwing velocity			Mean	SD	Throwing velocity			Mean	SD	Throwing velocity			Mean	SD
1	91.8	90.4	*	91.1	0.99	90.3	89.3	*	89.8	0.71	80.9	86.1	*	83.5	3.68	82.5	81.5	*	82	0.71
2	82.1	78.9	*	80.5	2.26	73.4	73	*	73.2	0.28	74.5	75	*	74.75	0.35	69.3	70.5	*	69.9	0.85
3	79.3	81.9	*	80.6	1.84	77.3	77.3	*	77.3	0.00	74	73.4	*	73.7	0.42	64.4	69.9	*	67.15	3.89
4	75.8	76.2	*	76	0.28	76	77.8	*	76.9	1.27	69.2	69.4	*	69.3	0.14	66.4	65.6	*	66	0.57
5	73.4	73.9	*	73.65	0.35	71.6	62.3	*	66.95	6.58	69.4	72.4	*	70.9	2.12	69.2	69.8	*	69.5	0.42
6	72	77.2	*	74.6	3.68	71.2	72.2	*	71.7	0.71	66.7	70.6	*	68.65	2.76	62.3	59.7	*	61	1.84
7	97.1	100	*	98.55	2.05	96.2	90.4	*	93.3	4.10	87.6	92.1	*	89.85	3.18	86.2	85.6	*	85.9	0.42
8	92.5	94.5	*	93.5	1.41	83.4	86.4	*	84.9	2.12	75.3	77.4	*	76.35	1.48	75.5	76.9	*	76.2	0.99
9	95.2	94.3	*	94.75	0.64	92.2	92.3	*	92.25	0.07	89.7	91.1	*	90.4	0.99	75.1	75.4	*	75.25	0.21
10	93.9	91.6	*	92.75	1.63	90	88.5	*	89.25	1.06	82.5	86.4	*	84.45	2.76	80.9	81.6	*	81.25	0.49
11	77.3	78.9	*	78.1	1.13	74.2	77.4	*	75.8	2.26	73.5	65.9	*	69.7	5.37	66.8	66.1	*	66.45	0.49
12	85.2	87.2	*	86.2	1.41	79.9	83.8	*	81.85	2.76	76.7	81.5	*	79.1	3.39	69.3	72.3	*	70.8	2.12
13	86.5	84.4	*	85.45	1.48	87.6	87.7	*	87.65	0.07	87.7	83.5	*	85.6	2.97	72.4	75.8	*	74.1	2.40
14	91.8	97.6	*	94.7	4.10	85.9	90.8	*	88.35	3.46	77.9	88.4	*	83.15	7.42	74.4	88.7	*	81.55	10.11
15	94.5	98.6	*	96.55	2.90	90.7	86.2	*	88.45	3.18	85.6	84	*	84.8	1.13	77.1	79.9	*	78.5	1.98
16	84.8	83.8	84.3	84.30	0.50	83	83	82.7	82.90	0.17	76.6	78.5	80.2	78.43	1.80	73.1	74.4	73.7	73.73	0.65
17	90.9	90.8	91.1	90.93	0.15	80,8	82.2	86	84.10	2.69	80.3	83.2	82.8	82.10	1.57	74.5	76.6	76.7	75.93	1.24
18	95.6	96.6	97	96.40	0.72	91.6	90.2	88.1	89.97	1.76	87	88.2	87.8	87.67	0.61	78.7	82	83.1	81.27	2.29
19	77.3	76.4	75.2	76.30	1.05	73	73.4	72.9	73.10	0.26	69.1	71.3	73.9	71.43	2.40	67	64.8	68.9	66.90	2.05
Total				**86.61**	**8.33**				**82.47**	**7.87**				**79.22**	**7.32**				**73.92**	**6.87**

Table 10. Values of maximal power output for each attempt and its corresponding velocity, acceleration and force. Maximal values of force, velocity and propulsive force.

Subject (ID)	Load (%RM)	Load (kg)	Velocity (ms)	Aceleration (m/s^2)	Force (N)	Power (W)	Fmax	Vmax	Fprop
1	41%	45	1.51	3.20	585.53	884.12	936.83	1.61	648.41
	41%	45	1.48	2.45	551.70	815.49	889.33	1.58	645.67
	61%	66	0.92	1.16	724.17	669.84	1041.70	0.95	781.61

	61%	66	0.90	2.08	785.06	704.39	1005.64	0.98	779.40
	61%	66	0.92	0.65	690.07	637.26	1043.27	0.93	761.67
	70%	76	0.85	1.38	850.76	726.22	1218.56	0.90	858.76
	70%	76	0.72	0.69	798.31	572.37	1239.85	0.75	824.86
	78%	85	0.53	0.97	916.46	482.13	1176.46	0.54	875.33
	78%	85	0.52	1.10	926.94	479.94	1155.37	0.53	870.19
	87%	95	0.72	1.05	1031.64	742.40	1377.41	0.74	1004.71
	87%	95	0.64	1.13	1039.34	669.28	1542.33	0.66	988.003
2	40%	40	1.63	3.33	525.59	857.70	994.91	1.75	579.50
	40%	40	1.63	2.03	473.48	773.67	1057.21	1.68	575.59
	60%	60	1.11	2.36	730.28	808.15	938.64	1.18	726.74
	60%	60	1.07	1.61	684.96	731.92	1081.48	1.10	708.86
	60%	60	1.06	1.87	700.76	739.85	1054.27	1.10	709.80
	70%	70	1.06	1.87	700.76	739.85	1171.84	1.02	797.25
	70%	70	0.89	1.88	818.11	731.07	1257.71	0.94	778.05
	80%	80	0.79	1.28	887.45	702.76	1213.65	0.83	866.70
	80%	80	0.80	1.33	890.95	713.15	1598.97	0.82	860.40
	80%	80	0.70	1.16	877.64	614.82	1574.52	0.74	842.82
	90%	90	0.50	0.72	947.38	472.54	1295.64	0.51	913.14
	90%	90	0.57	1.29	998.99	573.78	1051.07	0.59	952.16
3	44%	35	1.37	2.67	436.90	599.58	509.96	1.45	452.36
	44%	35	1.33	2.45	429.10	571.02	472.59	1.42	439.47
	58%	46	1.13	2.01	543.58	614.70	869.75	1.18	556.46
	58%	46	1.10	1.76	532.11	585.60	717.13	1.15	549.00
	58%	46	1.02	1.75	531.92	542.56	752.49	1.06	538.93
	70%	56	0.83	1.07	609.04	508.09	734.37	0.86	612.93
	70%	56	0.89	1.85	652.72	582.39	682.30	0.95	610.99
	75%	60	0.80	0.99	648.01	515.92	814.39	0.82	649.07
	75%	60	0.73	1.30	666.46	485.70	740.06	0.77	646.92
	75%	60	0.73	0.90	642.74	470.81	716.19	0.75	641.91
	88%	70	0.60	1.14	766.50	460.76	848.70	0.62	712.86
	88%	70	0.51	0.87	747.81	384.05	802.75	0.52	713.27
4	41%	30	1.60	3.24	391.50	625.83	599.27	1.69	433.09
	41%	30	1.54	3.42	396.78	609.39	589.79	1.63	429.92

	61%	45	1.16	2.37	547.97	636.08	685.27	1.22	537.83
	61%	45	1.11	2.49	553.41	611.88	904.56	1.16	522.57
	68%	50	1.00	2.56	618.66	615.59	643.45	1.06	566.96
	68%	50	0.92	2.19	599.85	552.61	744.82	0.97	569.37
	68%	50	0.88	2.25	603.23	532.72	628.88	0.95	560.88
	76%	56	0.92	1.75	647.41	594.86	785.29	0.95	612.43
	76%	56	0.86	1.95	658.46	569.56	758.27	0.91	608.01
	90%	66	0.82	1.50	746.50	613.74	869.27	0.84	719.53
	90%	66	0.71	2.24	795.49	564.93	971.12	0.77	688.11
	90%	66	0.69	1.79	765.51	529.73	812.37	0.40	675.16