

# **RATE OF FORCE DEVELOPMENT: RELIABILITY, IMPROVEMENTS AND INFLUENCE ON PERFORMANCE. A REVIEW**

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## **ABSTRACT**

Explosive muscular contractions are fundamental to sports activities such as sprinting, jumping or throwing. In these types of contractions the rate at which force is developed has been suggested to be the most important physical capacity. Therefore, the aims of these review was: to review the reliability of rate of force development (RFD) measures; to show the relationships between RFD and performance in specific sports movements; and to provide information about the response of RFD variables to different training interventions. From a total of 655 articles, after the exclusion criteria 60 articles were read. RFD has shown high to very high reliability in most of the studies, independently of the device used or the specific variable measured. The RFD at early time intervals has shown the higher correlations with performance in several sports movements. In addition, RFD at early time intervals has been shown sensitive to most training interventions, therefore, it seems to be the key point among RFD variables.

**Key Words:** power, strength, rate of force development, explosive force.

## **RESUMEN**

Las contracciones musculares de carácter explosivo son fundamentales en actividades deportivas tales como sprints, saltos o lanzamientos. En este tipo de contracciones, la ratio a la cual la fuerza es desarrollada ha sido sugerida como la capacidad física más importante. Por lo tanto, el objetivo de esta revisión fue: revisar la fiabilidad de las mediciones de la ratio de desarrollo de la fuerza (RFD); mostrar las relaciones entre la RFD y el rendimiento en movimientos deportivos específicos; y aportar información sobre la respuesta de variables de la RFD tras diferentes intervenciones de entrenamiento. De un total de 655 artículos, después de los criterios de exclusión, 60 artículos fueron leídos. La RFD ha mostrado fiabilidades entre altas y muy altas en la gran mayoría de los estudios, independientemente de la herramienta utilizada para la medición, o de la variable específica medida. La RFD en los primeros instantes del movimiento ha mostrado las mayores correlaciones con el rendimiento en varios movimientos deportivos. Además, esta RFD en los primeros instantes se ha mostrado sensible a la mayoría de las intervenciones de entrenamiento, por lo tanto, parece ser la variable clave dentro de la RFD.

**Palabras clave:** potencia, fuerza, ratio de desarrollo de la fuerza, fuerza explosiva

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## INTRODUCTION

The analysis of force-time curves has been widely used to evaluate neuromuscular function, highlighting the importance of force production capacity in specific time windows. This kind of analysis give us awareness, for instance, about the time required to achieve the peak force under isometric conditions (400 ms approximately). However, that time needed to achieve the development of this maximal force is significantly longer than the time duration of most specific sports movements. As a result of this short duration of several sports movements, the maximal force cannot be reached during the execution. For example, several sports movements such as sprints, changes of direction, throws, kicks, etc. involve contraction times lower than 250 ms (Rimmer & Slivert, 2000; Nunome, Asai, Ikegami & Sakurai, 2002). Consequently, maximal force parameter has lower importance when it is related to explosive strength, which reflects the ability to exert maximal force in minimal time. Of particular importance to sports scientists and coaches is the relationship between force-time curve variables an actual athletic performance measures. Contractile ratio of force development (RFD) is a major determinant of the maximal force and velocity that can be achieved during fast limb movements, therefore, RFD is inherently of major importance for athletes engaged in sports that involve such explosive type of muscle action (Aagaard, Simonsen, Andersen, Magnusson & Dyhre-Poulsen, 2002). For this reason a variable such as RFD is a key point to measure explosive strength. According to this, the aim of the present article is to review, the main ways to measure the RFD, the relevance of the RFD in sports, and the most used methods in the literature to improve this ability.

## METHOD

### *Literature screening*

A comprehensive searching for scientific literature relevant to this review was performed using MEDLINE, SCOPUS and Scholar Google databases (2004-2014, cute-off date September 30, 2014) and the terms “rate of force development” and “rate of torque development”. Relevant literature was also obtained from searches of related articles arising from the reference list of those obtained from the database searches.

### *Study selection for data extraction*

Study selection was accomplished through an abstract screening, excluding case reports, letters to editor, comments and reviews, animal studies, studies with non-healthy populations and studies with either young people (< 18 years old) or elder people (> 50 years old) . For inclusion in the subset of studies for data extraction, measurements of RFD or Rate of torque development (RTD) must have been collected. Reliability data, correlations with sports movements

or changes after a training intervention are required for including in this review.

### *Data retrieval*

The initial literature review identified 656 citations for screening. After reviewing the abstracts, 586 articles were rejected. Of the remaining 70 articles, 9 did not meet inclusion criteria. Finally, 61 articles were selected.

### RFD: CONCEPT AND CHARACTERISTICS

One of the most important studies about the RFD was written by Aagaard et al. (2002) who defined the RFD as the slope of the force-time curve obtained under isometric (IRFD) or dynamic conditions (DRFD). This parameter has been used to measure the ability to rapidly generate muscular force. The importance of RFD in sport movement with a time-limited force production has been mentioned, but RFD also plays a role in daily activities by improving the life quality in populations such as the elderly, reducing the risk of falls by fast activation of the muscles (Gruber, Gruber, Taube, Schubert, Beck & Gollhofer, 2007). Many types of movements, such as preventing a fall, are characterized by a limited time to develop force (0-200 ms). For this reason the ability to develop a rapid rise in muscle force may become more important than maximal muscle force in several situations. Nevertheless, in spite of the importance of RFD on several populations, this review is focused on young healthy people or athletes.

RFD is mainly related to neural activation. Particularly, within the neural factors, the firing frequency seems to be the most important parameter related to the RFD. The motor unit firing frequency (or discharge rate) can be up to 200 Hz during the onset of a maximum voluntary effort (Van Cutsem, Duchateau & Hainaut, 1998) with much lower rates at the time of peak force. Duchateau and Braudy (2014) showed that the increase in RFD during ballistic contractions was mainly due to adaptations in motor unit discharge rate. An increase in discharge rate from up to 100-200 Hz augmented substantially the RFD for all units of the pool. These data underscore the critical role of maximal motor unit discharge rate on the ability to rapidly develop force. In fact, the RFD continues to increase at stimulation rates higher than that needed to achieve maximum tetanic tension. It is possible, therefore, that supramaximal firing rates in the initial phase of a muscle contraction serve to maximize the RFD rather than to influence maximal contraction *per se*. It is possible that the firing of discharge doublets at the onset of contraction and during the phase of rising muscle force leads to enhance the initial generation of muscle contraction force, increasing the RFD (Aagaard, 2003).

In addition, the muscle size and fibre-type composition also play a role in the RFD (Aagaard et al, 2002). The firing frequency is related to fibre-type composition. Motor units with high axonal conduction velocity and short contraction time (type II myosin heavy chain) are responsible for higher RFD values. So, connections between fibre type and RFD have been found in several studies (Aagaard & Andersen, 1998; Andersen, Andersen, Zebis & Aagaard, 2010). Muscle size is another key point for RFD. The bigger size of type II muscle fibre together with the relevance of these fibres for the RFD, are the reason for the possible relations between muscle hypertrophy and RFD.

### RFD MEASURE

The ability of the human neuromuscular system for explosive force/torque production is typically measured by the RFD, because it is considered functional during explosive movements, such as sprinting, jumping or restabilizing the body after a loss of balance. RFD is calculated as the average slope of the moment-time curve during maximal efforts, and its values are expressed as  $N \cdot s^{-1}$

In regard to RFD measures, a great amount of variables should be taken into account. Throughout the literature, differences in variables such as the type of contraction (isometric vs dynamic), the device used to measure (force plate, strain-gauge, isokinetic dynamometer, linear position transducer), or the specific RFD variable [peak RFD, time to peak RFD (TPeakRFD), RFD at particular time intervals] are commonly found.

A key point when a measure is being carried out is their reliability (in the table 1 are shown a summary of the studies where the RFD measures reliability have been tested). Concerning the device reliability, historically the force plates and strain gauges have been widely the most used and reliable device when measuring RFD. On the other hand, other devices such as isokinetic dynamometers or linear position transducer have been also used by several researchers. Frequently, some controversy is generated when RFD is measured with a linear position transducer. Nevertheless, studies carried out with linear position transducer have shown high and very high reliability for almost all the RFD variables measured. Only in the study carried out by Chiu, Schilling, Fry & Weiss. (2004), a low reliability was found for the variable time to peak RFD (-0.03-0.72), however, the same variable showed such low reliability measured with a force plate (0.16-0.58). Regarding to isokinetic dynamometers reliability, unlike results have been shown by different studies. For instance Ingebrigtsen, Holtermann & Roeleveld (2009) and Prieske, Wick & Granacher (2014) did not find high reliability (0.69 and 0.68 respectively) for the peak IRFD during the curl biceps exercise. Conversely this same device has shown high ICC (0.93-0.99) for this same variable, measuring lower limb muscles (Maffiuletti, Bizzini,

Desbrosses, Babault & Munzinger, 2007; Muehlbauer, Gollhofer & Granacher, 2013).

Therefore, it seems that the reliability of RFD measures is more variable-dependent than device-dependent. In addition, most of the studies checking the RFD measures have been carried out performing movements that involve mainly the low limb muscles [countermovement jumps (CMJ), squat jumps (SJ), weightlifting movements], with only a minor part using the upper body muscles. Hence, more research is necessary involving upper body muscles to give knowledge about the reliability of RFD measures in these specific muscles.

TABLE 1  
Summary of studies analyzing the reliability of RFD measures.

Study	Type of movement	Device	Variable	Reliability (ICC)
Chiu et al. 2004	Dynamic: CMJ	Force plate (FP) & Linear position transducer (LPT)	Peak RFD, TPeakRFD, average RFD	FP: 0.91-0.95 (Peak RFD), 0.16-0.58 (TPeakRFD), 0.96-0.98 (average RFD) LPT: 0.89-0.94 (Peak RFD), -0.03-0.72 (TPeakRFD), 0.92-0.97 (average RFD)
Chiu et al. 2004	Dynamic: SJ	Force plate (FP) & Linear position transducer (LPT)	Peak RFD, TPeakRFD, average RFD	FP: 0.88-0.93 (Peak RFD), 0.91-0.97 (TPeakRFD), 0.9-0.95 (average RFD) LPT: 0.8-0.93 (Peak RFD), 0.81-0.93 (TPeakRFD), 0.7-0.93 (average RFD)
Kawamori et al. 2005	Dynamic: SJ	Force plate	Peak DRFD, TPeakDRFD	0.95 (Peak DRFD), 0.98 (TPeakDRFD)
McGuigan et al. 2006	Isometric: Midhigh pull	Force plate	Peak IRFD	> 0.96
Holtermann et al. 2007	Isometric: Leg extension	Strain gauge	RFD 0-300ms	0.88
Maffiuletti et al. 2007	Isometric and isokinetic: Knee extension (KE) and flexion (KF)	Isokinetic dynamometer	Peak IRTD, Peak DRTD	KE: 0.97-0.99 (Peak DRTD), 0.87-0.92 (Peak IRTD) KF: 0.97-0.99 (Peak DRTD), 0.9-0.91 (Peak IRTD)
McGuigan et al. 2008	Isometric: Midhigh pull	Force plate	Peak IRFD	> 0.96
González-Badillo et al. 2009	Dynamic: CMJ	Linear position transducer	Peak DRFD, RFD at peak force	0.88-0.97 (Peak DRFD), 0.87-0.96 (RFD at PF)

TABLE 1 (Cont.)

Ingebrigtsen et al. 2009	Isometric and isokinetic: curl biceps	Isokinetic dynamometer	Peak IRTD	0.69
Kraska et al. 2009	Isometric: Midhigh clean pull	Force plate	Peak IRFD	0.86
Stevenson et al. 2010	Dynamic: CMJ	Force plate	Eccentric DRFD, concentric DRFD	0.8-0.84 (eccentric DRFD), 0.78-0.83 (concentric DRFD)
Tillin et al. 2010	Isometric: Knee extension	Strain gauge	RFD 0-50, 50-100 and 100-150ms	Coefficient of variation: 12.8 (0-50), 5.7 (50-100) and 12.5 (100-150ms)
Comfort et al. 2011	Dynamic: Power clean, hang-power clean, midhigh power clean, midhigh clean pull	Force plate	Peak DRFD	0.92 (power clean), 0.95 (hang-power clean), 0.93 (midhigh power clean), 0.96 (midhigh clean pull)
McLellan et al. 2011	Dynamic: CMJ	Force plate	Peak DRFD, average DRFD	0.89 (Peak DRFD), 0.89 (average DRFD)
West et al. 2011b	Isometric: Midhigh pull	Force plate	Peak IRFD	0.89
Leary et al. 2012	Isometric: Midhigh pull	Force plate	Peak IRFD	> 0.81
Muehlbauer et al. 2013	Isometric: Plantar flexion	Isokinetic dynamometer	Peak IRFD	0.93
Marques et al. 2014	Dynamic: CMJ	Linear position transducer	Peak DRFD, TPeakDRFD	0.91 (Peak DRFD), 0.8 (TPeakDRFD)
Marques et al. 2014b	Dynamic: CMJ	Linear position transducer	Peak DRFD, RFD at peak force (PF)	0.98 (Peak DRFD), 0.93 (RFD at PF)
Prieske et al. 2014	Isometric: Curl biceps	Isokinetic dynamometer	Peak IRTD, IRTD at 30, 50, 100, 200, 300 and 400ms	0.68 (Peak IRTD), 0.76 (30ms), 0.8 (50ms), 0.85 (100ms), 0.95 (200ms), 0.96 (300ms), 0.97 (400ms)

## RELATIONSHIPS WITH PERFORMANCE

Traditionally, the RFD has been theoretically linked to performance in explosive/time-limited contractions or movements. In this way, several authors have explained the main reasons for this relationship.

For instance, Aagaard et al. (2002) presented the RFD as an important parameter with functional significance in fast and forceful muscle contractions. As several explosive movements such as sprint running, karate or boxing typically involve contraction times of 50-250 ms, any increase in contractile RFD becomes highly important as it allows reaching a higher level of muscle force in the early phase of muscle contraction. Due to this reasoning, Aagaard postulated contractile RFD as a major determinant of the maximal force and velocity that can be achieved during fast movements, and therefore, it is inherently of major importance for athletes engaged in sports involving explosive type of muscle actions.

In other example, Wilson, Lyttle, Ostrowski & Murphy (1995) proposed that, although in most sporting activities both the RFD and the maximum force produced are strongly related to performance, for explosive movements such as sprints, throws and jumps, in which force production times are on the order of 100 to 300 ms, the rate at which force is developed is suggested to be the most important physical capacity.

In a most recent article, Tillin, Jimenez-Reyes, Pain & Folland (2010) were in line with the previous arguments, postulating that explosive muscular contractions are fundamental to sports activities such as sprinting, jumping and punching, and included that are important for preventing injuries. As during explosive movements the time for the muscles to develop force is limited, the RFD is an important descriptor of performance in explosive contractions.

These kinds of arguments are commonly used in articles where the RFD is related with torque/force production in the early phase after the contraction onset. Nevertheless, when analyzing the relationships between the RFD and the performance in specific sport movements, the results are quite inconsistent. Below are shown the main results of the studies relating the RFD and the performance in such sport movements (table 2).

TABLE 2  
Summary of studies correlating RFD variables and performance.

Study	Sample	Ability	RFD measure	Results
Stone et al. 2004	Cyclists	Sprint cycling	Peak IRFD	$r = 0.28-0.39$
Haff et al. 2005	Weightlifters	Weightlifting	Peak IRFD	$r = 0.79$ (snatch RM) $0.69$ (clean and jerk RM)
Kawamori et al. 2005	Diverse athletes	CMJ, SJ	Peak DRFD	$r = -0.28-0.33$ (CMJ), $-0.45-0.39$ (SJ)
De Ruyter et al. 2006	Physically active	CMJ, SJ	IRFD (0-40ms)	$r = 0.76-0.86$ (CMJ), $0.75-0.84$ (SJ)
Kawamori et al. 2006	Weightlifters	CMJ, SJ	Peak IRFD, peak DRFD	IRFD: $r = 0.12$ (CMJ), $0.14$ (SJ) DRFD: $r = 0.65$ (CMJ), $0.74$ (SJ)
McGuigan et al. 2006	Wrestlers	CMJ	Peak IRFD	No correlations (data not shown)
Ebben et al. 2007	Track and field athletes	CMJ	Peak DRFD	$r = 0.19$
De Ruyter et al. 2007	Volleyball players	CMJ	Peak EERFD, peak IRFD	$r = 0.7$ (EERFD), $0.04$ (IRFD)
Ugrinowitsch et al. 2007	Power track athletes, body builders, physically active	CMJ	Peak DRFD	No correlations (data not shown)
McGuigan et al. 2008	Football players	CMJ	Peak IRFD	No correlations (data not shown)
Nuzzo et al. 2008	Football players, track and field athletes	CMJ	Peak IRFD (squat and midhigh)	Squat: $r = -0.045$ (JH), $0.78$ (JPP) Midhigh: $r = 0.35$ (JH), $0.65$ (JPP)
Storen et al. 2008	Runner athletes	Running economy	Peak DRFD	$R^2 = 0.26$
Kraska et al. 2009	Diverse athletes	CMJ, SJ	Peak IRFD	$r = 0.48$ (SJ), $0.66$ (LSJ), $0.43$ (CMJ), $0.62$ (LCMJ)
Sunde et al. 2010	Cyclists	Cycling economy	Peak IRFD	$R^2 = 0.58$
Khamoui et al. 2011	Physically active	Weightlifting	IRFD (0-50, 0-100ms)	$r = 0.49-0.52$ (DHP), $0.56$ (HPPF)
McLellan et al. 2011	Physically active	CMJ	Peak DRFD, average DRFD	$r = 0.68$ (Peak DRFD), $0.49$ (average DRFD)
Thompson et al. 2011	Football players	Level	TPeakRFD, RFD at 30, 50, 100 and 200ms	$ES = 0.82$ (TPeakRFD), $0.82$ (RFD at 30ms) $0.81$ (RFD at 50ms)
West et al. 2011	Swimmers	Swimming starts	Peak DRFD	$r = -0.56$ ( $p > .05$ )
West et al. 2011b	Rugby players	CMJ, 10m sprint	Peak IRFD	$r = 0.39$ (CMJ), $-0.66$ (10m sprint)



TABLE 2 (Cont.)

Leary et al. 2012	Golf players	Club head speed	Peak DRFD, DRFD at 30, 50, 90, 100 and 200ms	DRFD 0-150ms: $r = 0.38$
Tillin et al. 2012	Rugby players	CMJ, 5 and 20m sprint	Peak DRFD, DRFD at 50, 100, 150 and 200ms	DRFD 0-100ms: $r = -0.63$ (5m sprint), $-0.54$ (20m sprint) Peak DRFD 0-200ms: $r = 0.51$ (CMJ)
Muehlbauer et al. 2013	Physically active	CMJ	Peak IRFD	$r = 0.69$ (CMJPP), $0.63$ (CMJH)
Thompson et al. 2013	Football players	CMJ	Peak IRFD, IRFD at 30, 50, 100 and 200ms	$r = 0.48$ (peak IRFD), $0.62$ (0-30ms), $0.57$ (0-50ms), $0.52$ (0-100ms) and $0.54$ (0-200ms)
Marques et al. 2014	Physically active	CMJ	Peak DRFD, TPeakDRFD	$r = 0.83$ (Peak DRFD), $-0.81$ (TPeakDRFD)
Marques et al. 2014b	Diverse athletes	CMJ	Peak DRFD, TPeakDRFD	$r = 0.44$ (Peak DRFD) non significant, $0.03$ (TPeakDRFD)

*Note.* CMJH = countermovement jump height; CMJPP = countermovement jump peak power; EERFD: electrically evoked RFD; JH = Jump height; JPP = jump peak power; LCMJ: loaded countermovement jump; LSJ: loaded squat jump;

### Jumping ability

Jumping ability is clearly the most studied sports movement when talking about the relationships between RFD and sports performance. Since some years ago controversial results have been shown for this relationship. Thus, for isometric measures, 4 articles have shown positive correlations between peak IRFD and CMJ performance (Kraska et al. 2009; West et al. 2011b; Muehlbauer et al. 2013; and Thompson et al. 2013), whereas a similar number of articles have shown no correlations between these two variables (Kawamori et al. 2006; McGuigan, Winchester & Erickson, 2006; De Ruiter, Vermeulen, Toussaint & De Haan, 2007; McGuigan & Winchester, 2008 and Nuzzo, McBride, Cormie & McCaulley, 2008). In addition, IRFD at early time intervals has shown moderate (Thompson et al. 2013) to high (De Ruiter, Van Leeuwen, Heijblom, Bobbert & De Haan, 2006) correlations with CMJ performance. In the same line, DRFD has shown diverse relations with CMJ performance. Four studies found positive correlations between eccentric PRFD (De Ruiter et al. 2007), peak DRFD and average DRFD (McLellan, Lovell & Gass, 2011), peak DRFD and DRFD at early time intervals (Tillin et al. 2012), and peak DRFD and TPeakDRFD (Marques, Izquierdo, van den Tillaar, Moir, Sánchez-Medina & González-Badillo, 2014) and CMJ performance. On the other hand, there are four articles showing no

correlations between peak DRFD and CMJ performance (Kawamori et al. 2005; Ebben, Flanagan & Jensen, 2007; Ugrinowitsch, Tricoli, Rodacki, Batista & Ricard, 2007; Marques & Izquierdo, 2014).

Regarding to SJ performance, two studies showed significant correlations with both IRFD at early time intervals (De Ruyter et al. 2006) and peak IRFD (Kraska et al. 2009), while Kawamori et al. (2006) did not show correlations between peak IRFD and SJ performance. Finally, Kraska et al. (2009) studied the relation between peak IRFD and loaded jumps, finding significant correlations between peak IRFD and both loaded CMJ (0.62) and SJ (0.66).

### *Sprint ability*

Two studies were carried out looking for relationships between RFD and sprint performance. Both showed significant correlations between 10m sprint time and peak IRFD (West et al. 2011b), and between both 5 and 20m sprint time and DRFD at 0-100ms (Tillin et al. 2012).

### *Weightlifting*

There are a couple of studies checking the relationships between RFD variables and weightlifting abilities. Haff et al. (2005) showed high correlations between IPRFD and both snatch and clean and jerk 1RM. In the same way, Khamoui et al. (2011) found significant correlations between IRFD at early time intervals and both dynamic high pull (DHP) performance and high pull peak force (HPPF).

### *Cycling performance*

Stone et al. (2004) did not find correlations between peak IRFD and sprint cycling performance. In a different way, Sunde, Storen, Bjerkaas, Larsen, Hoff & Helgerud (2010) showed a very high relationship ( $R^2 = 0.58$ ) between peak IRFD and cycling economy.

### *Others*

The RFD variables have been also studied in relation with several performance indicators. Thus, Storen, Helgerud, Stoa & Hoff (2008) found peak DRFD related with running economy ( $R^2 = 0.26$ ), while West, Owen, Cunningham, Cook & Kilduff (2011) showed a moderate (0.56) but not significant correlation between peak DRFD and swimming starts. Leary et al. (2012) found significant correlations between DRFD at early time intervals (0-150ms) with swing speed. In a different way, Thompson et al. (2011) showed several RFD variables (peak DRFD, DRFD 0-30 and 0-50ms) as a good indicator of the football players' level.

### TRAINING INTERVENTIONS TO IMPROVE RFD

Growing interest has been given to the ability of the muscle to produce maximum power and high force values within short periods of time. Explosive muscle strength is considered to be of major importance in many sports that involve ballistic muscle contractions (Gruber, Gruber, Taube, Schubert, Beck & Gollhofer, 2007). Given the importance of the contractile RFD to movement capability, there is an obvious need to develop interventions to improve these performance parameters (Blazevich, Horne, Cannavan, Coleman, & Aagaard, 2008).

Through analysing the literature, different argumentations about the best way to improve the RFD have been shown. On the one hand, the use of heavy loads in strength training has shown to improve the RFD. Hartman, Bob, Wirth & Schimdtbleicher (2009) exposed that increases in RFD especially depends on the maximum effort of producing maximal muscle contraction speed regardless of actual movement velocity. This explains the positive training effect of maximum explosive strength actions with loads >90% of 1RM, on the power ability in the same movement.

On the other hand, other authors have postulated ballistic training as the best way to improve the RFD. Thus, Ricard et al. (2005) exposed that dynamic training promotes higher initial discharge rates by motor units, and increases motor unit synchronization during ballistic training, which enhances the RFD. Moreover, Gruber et al. (2007), stand for training with moderate loads accelerated with maximal effort to enhance RFD extensively compared to training with high loads, which improve maximal voluntary contraction (MVC) considerably, with only minor changes in RFD (Duchateau & Hainaut, 1984; Hakkinen and Komi, 1986).

Nevertheless, the influence of different strength-training modalities on explosive force production and its various determinants is still unclear (Tillin, Pain & Folland, 2012). Maybe one of the biggest problems is the lack of standardization in the strength-training modalities used in the literature to investigate the influence of strength training on RFD improvements. Throughout the analysis of the methods used by different researchers, it can be seen differences in training intervention duration (4-15 weeks), contraction types (isometric-concentric-eccentric), training intensity (maximal loads - heavy loads - light loads), exercises used (knee extension - squats - plantar/dorsal flexion - curl biceps - bench press) or training volume (number of days/exercises/sets/repetitions). Furthermore, differences in the way to measure the RFD are very usual: during isometric/dynamic contractions, peak RFD, time to peak RFD, RFD at different time intervals (30, 50, 100, 200....ms) or absolute RFD vs normalized RFD.

As a result of all of these experimental differences, unlike results have been shown from different researches. A summary of the data reported from studies aiming to improve the RFD with a training intervention are shown in table 3.

TABLE 3  
Summary of studies showing RFD responses after a training intervention.

Study	Sample	Intervention	Training	Results
Gruber et al. 2004	17 participants (5 males, 12 females)	4 weeks	2 days/week 60 min (postural stabilization tasks) 4 x 20" (20" rest)	↑ peak RFD ( $p < .05$ ) RFD ↑ at 30 and 50 ms ( $p < .05$ ) No changes in time to peak RFD No changes in RFD at times longer than 100 ms
Barry et al. 2005	16 males (8 young, 8 elderly)	4 weeks	3 days/week 4 x 6 (40 to 100% MVC) (1-2' rest) Young group (YG) and elderly group (EG) Unilateral elbow flexion	Peak RTD ↑ in both groups ( $p < .05$ ) YG ↑ RTD at 100 and 200 ms ( $p < .05$ ) EG ↑ RTD at 200 ms ( $p < .05$ )
Kyrolainen et al. 2005	23 males	15 weeks	2 days/week 80-180 repetitions/session Jumping exercises (D, SJ HJ, HDJ)	Peak RFD ↑ after 10 weeks ( $p < .05$ )
Del Balso et al. 2007	20 males	4 weeks	3 days/week 6 x 10 MVCs (3-4") (2' rest between sets) Unilateral plantar flexion	Peak RFD ↑ $42.5 \pm 13.3\%$ ( $p < .05$ ) ↑ RFD correlated with ↑ rate of muscle activation ( $r = .95$ )
Gruber et al. 2007	33 participants (17 males, 16 females)	4 weeks	Sensoriomotor training group (SMT): 4 stabilization tasks, 4 x 20" (40" rest) Ballistic training (BST): 2 exercises 2 x 10 (30-40% RM) Control group (CG)	Peak RFD ↑ in SMT and BST groups ( $p < .05$ ) Time to peak RFD ↓ in SMT and BST groups ( $p < .05$ ) Peak RFD ↑ in BST vs SMT groups ( $p < .05$ )
Holtermann et al. 2007	24 males	3 weeks	3 days/week 5x10 MVC Plantar flexion	RFD 28.4% ↑ at 300 ms ( $p < .01$ )

TABLE 3 (Cont.)

Holtermann et al. 2007b	14 males	1 week	9 sessions/week 5x5 MVC Ankle dorsiflexion	↑ Peak RFD, RFD at 0-50, 0-100 and 100-200ms ↓ RFD at 200-300 and 300-400ms
Adamson et al. 2008	10 females	8 weeks	3 days/week 5 x 5 RM (2-3' rest) Unilateral curl biceps	Peak RFD ↑ 40-60% (trained arm), 30-55% (untrained arm)
Blazevich et al. 2008	33 participants (16 males, 17 females)	10 weeks	3 days/week 4 x 6 RM (weeks 1-3), 5 x 6 RM (weeks 4-7), 6 x 6 RM (weeks 8-10) Concentric (CON) and eccentric group (ECC) Isokinetic knee extension (30°·s <sup>-1</sup> )	RFD ↑ at 30, 50, 100 and 200 ms in CON and ECC groups RFD at 30 ms ↑ in CON vs ECC groups ( <i>p</i> < .05)
Haff et al. 2008	6 female athletes	11 weeks	Non specified Exercises: clean, clean and jerk, snatch, clean pull, snatch pull, squat and front squat	No changes in peak IRFD or peak DRFD Peak IRFD inversely related to volume load (VL): ↑ 5.1% when VL ↓ 57.5%
Storen et al. 2008	17 runner athletes	8 weeks	3 days/week 4x4 RM Half squats	Peak RFD ↑ 26%
Winchester et al. 2008	14 males	8 weeks	3 days/week 3 x 3-12 (26-48% RM) Jump squat	Peak IRFD ↑ 49%
Blazevich et al. 2009	14 participants (non specified)	5 weeks	3 days/week 4 x 6 RM (weeks 1-3), 5 x 6 RM (weeks 4-5) Concentric (CON) and eccentric group (ECC) Isokinetic knee extension (30°·s <sup>-1</sup> )	RFD ↑ 16% (-56.9/+72.4%) at 30 ms and 2.4% (-19/+28.8%) at 200 ms RFD at 30 ms inversely related to the moment-angle shift ( <i>R</i> <sup>2</sup> = .50)
Hartman et al. 2009	40 males	14 weeks	3 days/week Strength-power group (SPP): hypertrophy + strength-power phase Daily undulating periodization (DUP) Bench press	No changes in peak RFD in SPP and DUP groups High variability in peak RFD changes: 7.06 ± 36.46% (SPP group), 1.61 ± 21.71% (DUP group)

TABLE 3 (Cont.)

Ingebrigtsen et al. 2009	39 males	3 weeks	3 days/week High-load slow-contraction group (HS), high-load fast-contraction group (HF) and low-load fast-contraction group (LH) Elbow flexions	No changes in peak IRFD No differences between training groups
Lamont et al. 2009	30 males	6 weeks	2 days/week 3-4 x 3-6 (55-90% RM) Squat training (SQT) and squat + vibration training (SQVT) Half squats	↑ IRFD initial in SQTV ( $p = 0.041$ ) No differences in RFD at 30, 50, 80, 100, 150 and 250 ms
Andersen et al. 2010	25 males	14 weeks	3 days/week (38 sessions) 4 x 10-12 RM (sessions 1-15), 4 x 8-10 RM (sessions 16-25), 5 x 6-8 RM (sessions 26-38) 4 leg exercises	RFD ↑ 11% at 250 ms ( $p < .05$ ) RFD/MVC ↓ 10-18% at time intervals up to 140 ms ( $p < .05$ ) ↓ RFD/MVC at 50 ms correlated with ↓ in type IIX muscle fibers ( $r = .61$ )
Sunde et al. 2010	16 cyclists (12 males, 4 females)	8 weeks	3 days/week 4 x 4 RM Half squats	Peak IRFD ↑ 16.7% ( $p < .05$ )
Vila-Cha et al. 2010	27 males	6 weeks	3 days/week Strength group (SG): 3-4 x 8-15 (60-85% RM), endurance group (EG): 20-50 min 50-70% HRR	Peak IRFD ↑ 33.3% ( $p < .05$ ) in SG
Marshall et al. 2011	32 males	10 weeks	2 days/week 1 x 8 RM (G1), 4 x 8 RM (G4), 8 x 8 RM (G8) Half squats	Peak IRFD, IRFD at 30 and 50ms ↓ in all groups
Kramer et al. 2012	32 participants (18 males, 14 females)	4 weeks	3 days/week Training group: 5 x 20 jumps (sledge jump system)	Peak DRFD ↑ 35% ( $p < .05$ )
Lamas et al. 2012	40 males	8 weeks	3 days/week Strength group (SG): 4-8 x 4-10 RM, power group (PG): 4-8 x 30-60% 1RM Half squats	Peak DRFD (SJ) ↑ 42% (SG) and 24% (PG) No changes in peak DRFD (CMJ)

TABLE 3 (Cont.)

Ronnestad et al. 2012	18 males	12 weeks	2 days/week 3 x 4-10 RM (S group), 3 x 4-10 RM + endurance training (S+E group) Half squats, leg press, ankle plantar flexions	Peak IRFD ↑ 15% (S) with no changes in S+E group
Behrens et al. 2013	20 participants (13 males, 7 females)	8 weeks	2 days/week 3 x 6-7 jumps (CMJ, SJ, DJ)	IRFD at 30 ms ↑ (p = 0.033)
Heggelund et al. 2013	8 males	8 weeks	3 days/week 3 x 10 RM (CON leg), 4-5 x 5 RM (MST leg) Leg extensions	Peak IRFD and peak DRFD ↑ in both groups (p < .05) MST leg ↑ more peak DRFD (p = 0.044) and peak IRFD (p = 0.053)
Oliveira et al. 2013	19 males	6 weeks	3 days/week 3 x 6-10 MVC Knee extension	No changes in peak IRFD RFD ↑ 28% (0-10ms) and 22% (0-20ms)
Farup et al. 2014	14 males	10 weeks	3 days/week 4-5 x 4-10 RM (RT group) or endurance group (END group)	Normalized RFD ↓ at 30, 50, 100 and 200 ms (knee flexors) and at 200ms (knee extensor) in both groups

*Note.* DJ = Drop jump; HDJ = Hurdle jump; HJ = Hop jump; HRR = Heart rate reserve

The summary of the main findings are commented below, divided into the adaptations on specific RFD measures.

### *Peak RFD*

Regarding to changes in peak RFD, 14 articles showed improvements in this variable after the training interventions. These improvements in peak RFD have been shown after significant different training interventions, such as sensorimotor training (Gruber et al. 2004; Gruber et al. 2007), plyometrics (Kyrolainen et al. 2005; Kramer, Ritzmann, Gruber & Gollhofer, 2012), heavy loads (Adamson, MacQuaide, Helgerud, Hoff & Kemi, 2008; Storen et al. 2008; Sunde et al. 2010; Lamas et al. 2012; Ronnestad, Hansen & Raastad, 2012; Heggelund, Fimland, Helgerud & Hoff, 2013), hypertrophy training (Vila-Cha, Falla & Farina, 2010; Heggelund et al. 2013) MVCs (Del Balso & Cafarelli, 2007), ballistic training (Gruber et al. 2007; Winchester et al. 2008), power training (Lamas et al. 2012) and after training with a wide range of intensities (Barry, Warman & Carson, 2005).

Among the training interventions showing no improvements in peak RFD, it has been also found several training methodologies, such as weightlifting training (Haff et al. 2008), both heavy loads and power training (Ingebrigtsen et al. 2009; Lamas et al. 2012), hypertrophy training (Marshall, McEwen & Robbins, 2011), MVCs (Oliveira, Oliveira, Rizatto & Denadai, 2013) and after a periodized strength period with phases of both hypertrophy and power training (Hartmann, Bob, Wirth & Schmidtbleicher, 2009).

#### *Time to peak RFD*

Only both studies carried out by Gruber et al. evaluated changes in time to peak RFD, showing unlike results. While no changes were found after training interventions performing tasking stabilization tasks (Gruber et al. 2004), lower times required to achieve the peak RFD were found after quite similar stabilizations tasks and after a ballistic training (Gruber et al. 2007).

#### *RFD at early time intervals*

This parameter seems to be more sensitive to a period of training intervention. Thus, seven articles have shown improvements in this variable at 10 and 20 ms (Oliveira et al. 2013), 30 ms (Behrens, Mau-Moeller & Bruhn, 2013), 30 and 50 ms (Gruber et al. 2004), 30, 50, 100 and 200 ms (Blazevich et al. 2008), 30 and 200 ms (Blazevich et al. 2009), 50, 100 and 200 ms (Holtermann, Roeleveld, Vereijken & Ettema, 2007), and at 100 and 200 ms (Barry et al. 2005).

Nevertheless, there were three articles founding no changes in RFD at early time intervals: Lamont, Cramer, Bembem, Shehab, Anderson & Bembem (2009) at 30, 50, 80, 100, 150 and 250 ms; Marshall et al. (2011) at 30 and 50 ms; and Farup, Sorensen & Kjolhede (2014) at 30, 50, 100 and 200 ms.

This disagreement in the improvements in RFD at early time intervals could be explained by differences in the training interventions. While in the studies where the RFD at early time intervals showed improvements the training interventions consist of heavy loads, MVCs, plyometrics, or ballistic training, in the studies in which RFD at early time intervals did not show changes were used hypertrophy loads. Regarding to this, Andersen et al. (2010) found that decreases in RFD at early time intervals can be explained by a parallel decrease in the area of type IIX muscle fibers ( $r = .61$ ). As a training intervention focusing in hypertrophy usually leads to a decrease in type IIX muscle fibers, it seems logical the lack of improvements in RFD at early time intervals showed in these three studies.

In addition, two studies measured the RFD average in a wide period of time, showing both improvements in the values of the RFD at 0-300 ms (Holtermann, Roeleveld, Engstrom & Sand, 2007) and at 0-250 ms (Andersen et al. 2010).



## CONCLUSIONS

### *Measures*

Isometric contractions have been clearly the most usual way of measuring RFD compared to dynamic contractions. This is probably because of the better standardization of the protocol and the greater control of isometric actions in contrast of dynamic ones. In relation to the device employed to measure the RFD, force plate seems to be the better option due to the possibility of measuring both isometric and dynamic actions (isokinetic and non isokinetic) , but strain gauges linear position transducers and isokinetic dynamometers have also shown good reliability.

Relative to the specific RFD variable measured, an evolution can be seen. At the beginning of RFD studies, most of them were focused on both peak RFD and time to peak RFD, but over the years, growing interest has appeared on the RFD at early time intervals.

### *Relationships with sport performance*

Generally, unclear results have been observed in different studies, independently of the type of contraction (isometric vs dynamic), ability (i.e. jumping, weightlifting, running sprint, cycling sprint) or population (athletes vs recreational). So, there is no clear the influence of parameters such as peak RFD or time to peak RFD on sports performance. Nevertheless, it seems clearer that the ability to produce high RFD at early time intervals (i.e. 0-100ms) is related to the performance in several sports movements.

### *RFD improvements*

After analysing the RFD response following a training intervention, the parameter seeming to be more sensitive is the ability to develop higher RFD at early time intervals. Peak RFD have also shown improvements after most of the training interventions found in the literature, while time to peak RFD have received lower attention, being measured only in two studies and showing improvements in one of them.

Finally, as RFD at early time intervals have shown both the higher correlations with sports performance and the greater response after a training intervention, this seems to be the key point within RFD variables. Therefore, researchers and coaches must be aware of the importance of RFD at early time intervals and, accordingly, this parameter should be measured during functional tests. In addition, coaches should pursued improvements in this variable because of its relationship with several sports movements.

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