ESCUELA INTERNACIONAL DE DOCTORADO
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Directores:
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AUTHORIZATION OF THE DIRECTORS OF THE THESIS FOR SUBMISSION

Prof. Dr. Pedro E. Alcaraz Ramón and Prof. Dr. Julio Calleja González as Directors of the Doctoral Thesis "Acute effects and short-term adaptations following different strength and power-oriented resistance training protocols in basketball players" by D. Tomás Trindade de Freitas in the Programa de Doctorado en Ciencias del Deporte, **authorize for submission** since it has the conditions necessary for its defense.

Sign to comply with the Royal Decrees 99/2011, 1393/2007, 56/2005 and 778/98, in Murcia, March 11th, 2019.

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As basketball, research in the field of Sport Science is a team-sport. Most importantly, the process of obtaining a doctoral degree is a "game" that you simply can't win on your own. It requires a huge team effort and it is only possible if you are part of a winning team. Therefore, I would like to acknowledge my "teammates" without whom this PhD thesis would have never seen the light of day.

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“Challenges are what make life interesting and overcoming them is what makes life meaningful.”

Joshua J. Marine

This thesis is a compendium of 3 articles already published in peer-reviewed journals. The references for the abovementioned articles are as follows:

Article 1

Freitas TT, Calleja-González J, Alarcón F, Alcaraz PE. Acute effects of two different resistance circuit training protocols on performance and perceived exertion in semiprofessional basketball players. J Strength Cond Res. 2016;30(2):407-14.

Article 2

Freitas TT, Martinez-Rodriguez A, Calleja-González J, Alcaraz PE. Short-term adaptations following Complex Training in team-sports: A meta-analysis. PloS One. 2017;12(6):e0180223.

Article 3

Freitas TT, Calleja-González J, Carlos-Vivas J, Marín-Cascales E, Alcaraz PE. Short-term optimal load training vs a modified complex training in semi-professional basketball players. J Sports Sci. 2019;37(4):434-42.

INDEX

ABBREVIATIONS

The abbreviations of the units from the International System Units are not included in the following list as there are internationally accepted standards for their use. In addition, no abbreviations universally used in statistics are presented in this section.

AV	Average velocity
CA	Conditioning activity
CG	Control group
CMJ	Countermovement jump
COD	Change of direction
CT	Complex Training
D1	Division I
HRC	High-Intensity Resistance Circuit Training
ICRI	Intracomplex rest interval
MCT	Modified Complex Training
MPV	Mean propulsive velocity
OLT	Optimal Load Training
PAP	Postactivation potentiation
PCT	Power Circuit Training
PDec	Performance decrement
REST	Resting conditions
RFD	Rate of force development
RM	Repetition maximum
RPE	Rating of perceived exertion
RSA	Repeated sprint ability
S&C	Strength and conditioning
SLJ	Standing long jump
U-D1	Under-Division I
VJ	Vertical jump

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

I - INTRODUCTION

I. INTRODUCTION

Basketball is a team-sport that incorporates aerobic and anaerobic metabolic processes characterized by intermittent high-intensity actions such as jumping, sprinting, shuffling or changing direction (1-4). Furthermore, it is a sport that requires a complex combination of individual technical skills, team strategies, tactics and psychological and motivational aspects (1, 4). In the recent years, there has been a clear increase in the physical demand of the competition due to changes in regulations and tactical evolution of the game (5-7). These changes include a decrease on the available time to attack the basket from 30 to 24 s, a reduction in the time spent on the backcourt from 10 to 8 s as well as a different subdivision of the game into four 10 min quarters instead of two 20 min halves (7).

Time-motion analysis has shown that during a basketball game, the total number of movements performed by players depends on the competition level (8). According to Ferioli et al. (8), higher level competitors execute a mean of 703 movements, performing over 100 high-intensity actions per minute of playing time. Of note, players perform more than one jump per minute played (an average of more than 27 during a match) (8) and are involved in high-intensity running activities, such as sprinting, every 39 s (1). In this regard, jumping capability (9, 10), the ability to perform repeated sprint efforts (11-13) and change of direction (COD) ability (4, 9, 10) are amongst the most important determinants of high performance in basketball. Different studies (9, 10) have shown that better players tend to display higher neuromuscular performances measured by the means of strength, vertical jump (VJ), sprint, repeated sprint, and COD abilities. In particular, considering VJ, differences of 8.8% in jump height have been reported between elite players and average-level practitioners (9). Similar conclusions were drawn concerning COD ability, as differences of 6.2% were found in COD tests outcomes among athletes with different skill levels (9). Therefore, based on the match-demands data and the evidence of superior neuromuscular performance in basketballers of higher competition level, it can be inferred that the development of physical capabilities is crucial in this sport, as it may allow players to run faster and jump higher than the opponents, to sustain match-related contacts and hits and, ultimately, exploit their technical and tactical skills during a game (14).

As a consequence, to face the increasing physical demands of competition, the development of strength and conditioning (S&C) programs in basketball has become common practice in every competition level and age category (5, 14-20). At the professional level, a study reporting the practices of the National Basketball Association's (NBA) S&C professionals highlighted that the main focus of the physical preparation programs is on strength and power development and speed and plyometric training (15). The results from Simenz et al. (15) emphasize that resistance training protocols are employed by practitioners to improve basketball players' athletic performance during the in-season period. In addition, resistance training has also been considered a key injury prevention strategy (21, 22) and, thus, coaches and sports scientists must properly manage resistance training loads to optimize performance and minimize injury risk. However, practitioners face several problems when implementing said resistance training protocols such as the congested and long competition schedules, the limited time available in the weight room (15) and the need to manage the high workloads that players are submitted to during the season that result in cumulative fatigue (23-26).

In fact, due to the congested fixtures of a basketball season, fatigue management and recovery are crucial to ensure that athletes can stay injury-free (5, 23), cope with match demands and perform at the top of their physical abilities (24, 25). For this reason, and keeping in mind that the significant amount of high-intensity actions (i.e. jumps, sprints, COD, etc.) and contacts/hits that occur during practice and competition can potentially create muscle damage or trauma (26), it is important to also consider the acute effects of the resistance training sessions completed during the competitive phase of the season (25). On this matter, to ensure adequate recovery from basketball-related and resistance training activities, as well as optimal adaptations, it is necessary to know the type and time-course of the induced fatigue (e.g., acute and/or residual), its underlying mechanisms (24, 27) and the potential decreases in performance associated with its accumulation (25, 26, 28).

The issue with fatigue is that it consists on a complex phenomenon that involves different components and acts on numerous sites within both the central nervous system (central fatigue) and the skeletal muscle (peripheral fatigue) (28-31). Central fatigue is associated to muscle force decrements due to a decreased neural drive from the motor cortex of the brain (28-30). This fatigue mechanism leads to a reduction on the number of functioning motor units and to a decrease on motor units firing frequency. Peripheral fatigue, on the other hand, is related to an impaired muscle contractile function that results in reduced muscle fiber force (28, 32, 33). This phenomenon is believed to occur due to impaired neuromuscular transmission, to the failure of muscle action potentials or to impaired excitation-contraction coupling (30, 32). Nevertheless, it is important to understand that fatigue, defined as an exercise-induced reduction in the ability to exert muscle force or power (29), refers to a combination of acute effects that can impair performance and not to a single mechanism that explains, by itself, the declines observed (30, 32).

According to Enoka et al. (30), fatigue is task-dependent, meaning that the characteristics of the task such as the pattern of muscle activation or motor command, the intensity and duration of the activity or the velocity of contraction or execution influence the fatigue mechanism that occurs. Thus, coaches and sport scientists should focus on assessing not only competition and basketball practice-induced fatigue (23-25) but also the fatigue elicited by resistance training (34-38) as its characteristics (i.e., muscle activation patterns, duration and velocity of contraction, etc.) are notoriously different (39).

From an applied perspective, given that assessing the specific fatigue mechanisms (i.e., central or peripheral) is methodologically complex and time consuming (29, 37), fatigue can be defined, on a more global manner, as an exercise-induced decline on performance (28). Lowered work rate during competition, reduced total distance covered, reduced proportion of time spent sprinting or on high-intensity activities are common manifestations of fatigue (28) that practitioners should be aware of. In addition, reduced technique outcomes can also be considered indicators of fatigue on team-sports (28, 40, 41). Knicker et al. (28), after reviewing several studies conducted in various sports, concluded that in soccer, kicking speed, passing and shooting accuracy declined under fatiguing conditions and that in rugby and cricket, technique outcomes were also reduced. Regarding basketball, Lyons et al. (40), Chen et al. (41) and Supej (42) all reported similar conclusions that, under fatiguing conditions, technical skills (namely passing and shooting) were affected. Of note, Edwards et al. (25) suggested that session rating of perceived exertion (RPE), VJ outcomes, wellness questionnaires, sprinting ability, resting heart rate, heart rate variability and biochemical markers (i.e. testosterone, cortisol and creatine kinase) can be considered easy-to-use monitoring tools for basketball match and training-induced fatigue.

As previously stated, basketball is a complex modality in which, apart from technical and tactical aspects, physical factors such as VJ, sprint, repeated sprint and COD abilities are crucial for performance (4, 9-13). In this context, the high neuromuscular demands of this sport become clear (4, 8, 10) and it is evident that sport-specific stimulus alone is not enough to optimize players' athletic performance (10, 14). For such a reason, resistance training is usually performed as a complement to field work in team-sports (5, 15, 16, 38, 43-45). Hence, when monitoring neuromuscular fatigue, coaches should be aware that the acute effects of, for example, strength and power training must not be neglected.

In reality, resistance training is commonly used by S&C coaches since a compelling body of literature has shown that it is effective in increasing muscular strength and power, hypertrophy, local muscular endurance, balance and coordination (46, 47). Even though all these physical qualities contribute to athletic performance, muscular strength, defined as the ability to exert force on an external object or resistance (47, 48), could be considered one of the most important because it serves as foundation for other qualities and for several general sport skills (47, 49-51). For instance, muscular strength is thought to be the physical quality that most underpins neuromuscular power (49). According to Cormie et al. (49), there is a fundamental relationship between these qualities, which dictates that an individual cannot possess a high level of power without being relatively strong. Firstly, because stronger individuals tend to present enhanced total muscle and myofibrillar cross-sectional area of type I and, to a greater extent, type II fibers (49). Secondly, because it is believed that pennation angle and possibly fascicle length may also be greater in these subjects (49). Additionally, neural drive, as well as inter- and possibly even intra-muscular coordination, has been found to be superior after 3 years of resistance training which possibly results in a shift in the force-velocity relationship. This means that the force generated by the muscle might be greater for any given velocity of shortening. As a result, maximal neuromuscular power output would be superior following long periods of maximal strength training (49). Keeping in mind that most sport-specific skills take place in very short periods of time and the ability to produce force quickly is vital for athletic performance (46, 49), increases in strength and, subsequently in power, are crucial.

Remarkably, a relevant review by Suchomel et al. (47) also showed that greater muscular strength is associated to enhanced force-time characteristics and neuromuscular performance (i.e. sprinting, jumping and changing direction) in a multitude of sport modalities. To clarify this notion, and using the back squat as a reference, the authors state that lifting at least two times one's body mass may be an indicative of a greater performance (47) as there is evidence that individuals who are able to do it produce greater lower-body mechanical power in dynamic actions (52), jump higher and sprint faster (53). The theoretical relationship between relative back squat strength and performance outcomes is presented in Figure 1, adapted from Suchomel et al. (47).

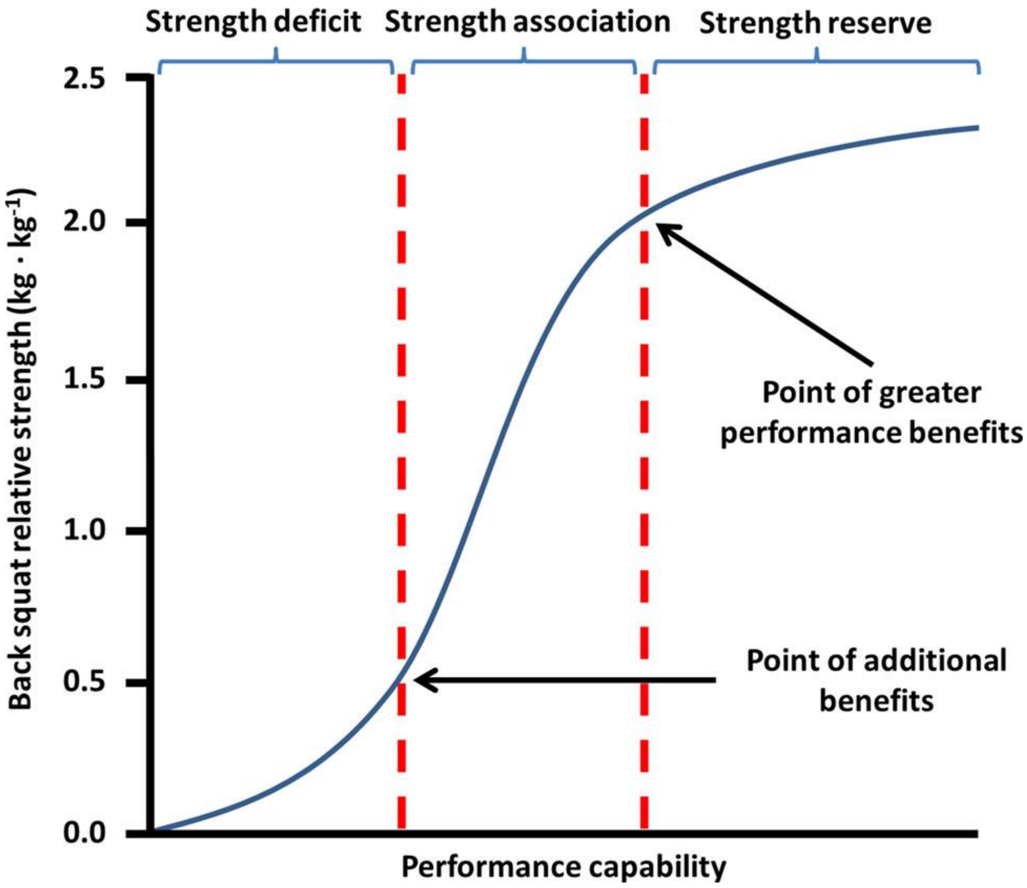

Figure 1. Theoretical relationship between back squat relative strength and performance capability, from Suchomel et al. (47).

According to this relationship, three distinct phases can be identified: strength deficit, strength association and strength reserve. The first phase, strength deficit, corresponds to the motor learning phase and is usually predominant in novice athletes that are not able to exploit their strength levels and translate them into performance increments. The second phase, strength transition, is characterized by a nearly linear relationship between strength and performance which implies that increases in strength often translate “directly” into performance increments. The final phase, strength reserve, is reached when athletes are able to squat two times their body mass. During this phase, increases in maximal strength may not translate as easily into performance benefits and athletes’ focus should be placed on maintaining strength levels (instead of increasing them), and developing other physical qualities such as power or rate of force development (RFD) (47). However, it is important to state that this relationship is purely theoretical and that the threshold presented (two times body mass) should be interpreted as a general guideline since solid practical and applied evidence still lacks (47). Nevertheless, it is recommended that players should become as strong as possible in the context of their sport since strength acts as the "vehicle" driving the improvement of key performance variables such as RFD and power (47, 54, 55). When it comes to basketball, different studies support the relationship between strength and performance outcomes. For example, maximal dynamic strength has been identified as the best predictor of 5 and 10 m sprint performance (50), as an important determinant of COD ability (51) and has been associated to superior VJ performance in basketballers (56, 57).

Also worth noting, is the fact that muscular strength has been linked to an increased robustness and to a reduced risk of injury (21, 47, 58). A recent investigation concluded that stronger team-sports players were able to better tolerate larger week-to-week changes in workload and were at a reduced risk of injury for any given workload when compared to their weaker counterparts (58). These findings suggest that the workload-injury relationship can be moderated by strength. Thus, players should be involved in adequate resistance training programs throughout the season in order to increase strength levels that, ultimately, enable them to tolerate higher match-based loads (58). For the reasons stated above, the development of muscular strength is fundamental in a team-sports setting and sport scientists and S&C coaches should apply appropriate resistance training programs during the season.

In connection with the previous, a classic study by Caterisano et al. (59) investigated the effects of a basketball season on strength parameters in Division I college players and reported a significant decrease in upper- and lower-body strength, measured with the bench press and leg press 1-repetition maximum (RM), respectively, from pre- to post-season. Importantly, the decrements in maximal strength occurred despite players being involved in a resistance training program during the season (59), which suggests that the strength training stimulus imposed was not effective. This is problematic, particularly considering that maintaining or increasing strength throughout a basketball season is essential for performance and player availability (10). Therefore, to optimize adaptations and counteract possible strength losses as the season progresses, several studies have investigated the effects of different resistance training programs on strength and performance outcomes in team-sports (5, 15, 16, 38, 43-45).

Hermassi et al. (43), for example, concluded, with a sample of elite handball players, that heavy resistance training improved maximal strength, peak power in upper- and lower-limbs and sprint velocity. Athletes from the testing group performed an 8-week biweekly heavy resistance program and results indicated that upper-body peak power increased from 477 ± 98 W to 532 ± 87 W and lower-body peak power from 681 ± 122 W to 763 ± 121 W. The half-squat 1RM improved from 181 ± 11 kg to 198 ± 9 kg and bench press 1RM from 80.4 ± 5.0 kg to 96.2 ± 3.6 kg. For all the same variables, the control group's values remained unchanged or even decreased (43). Another study conducted in-season with soccer players, that also used heavy loads (equivalent to 6RM), reported increases in maximal strength (i.e., the 1RM on the exercises performed) and no negative effects on VJ performance (38). Based on these findings, it appears that it possible to counteract strength losses during the competitive period of the season in different team-sports modalities by using heavy resistance training.

In this respect, High-Intensity Resistance Circuit Training (HRC) has been proposed as an effective and time efficient method (38, 60-63). Briefly, the HRC presents the main characteristics of traditional circuit training regarding the dynamic of the workout bout as exercises are performed in sequence with short rest periods between them. In the protocol initially presented by Alcaraz et al. (60), and later replicated in other studies with recreationally active males (61, 64, 65) and team-sports athletes (38), exercises were performed with loads corresponding to 6RM, which is equivalent to 85-90% of 1RM. For this reason, HRC has been found to promote strength adaptations similar to those obtained with a traditional heavy resistance training, with the upside of being completed in a shorter time (38, 60). To be precise, in the study by Alcaraz et al. (60), the HRC bout consisting of 3 sets was performed in 55 min while the traditional strength workout, with the same number of sets and repetitions, lasted 105 min. Such findings are promising and support the notion that this method may be useful in a team-sports setting, in which the time available for resistance training is limited (15).

Another advantage of the HRC is related to the fact that this training has been shown to promote greater adaptations in cardiorespiratory parameters in soccer players, following an 8-week intervention, in-season, when compared to a traditional non-circuit-based strength training performed with the same relative load (6RM) (38). According to the author, these results can be explained by the higher activation of the cardiorespiratory system during and immediately after a session of HRC, highlighting a significantly higher residual effect of this protocol when compared to said non-circuit-based strength training (38). In summary, HRC has the potential to increase maximal strength similarly to traditional strength protocols while producing higher cardiorespiratory adaptations in a more time efficient manner in team-sports athletes (38).

However, several studies on the acute physical and physiological effects of a HRC exercise bout have reported that this circuit-based training is quite demanding for the athlete when compared traditional strength training programs (34, 38, 66). Marín-Pagán (38) concluded that an HRC session, consisting on 3 sets of 6 exercises, divided into two blocks, resulted in higher heart rate during and after the session, augmented blood lactate concentration, relative energy cost and excess post-exercise oxygen consumption, indicating a greater aerobic and metabolic stress. Furthermore, increased RPE and impaired force production capability, induced by peripheral fatigue mechanisms, have also been described following an acute bout of HRC (34). Altogether, these findings suggest that HRC, despite being an effective and time efficient method to increase strength and cardiorespiratory fitness (38, 60), may lead to important levels of fatigue. As such, coaches and sport scientists should be aware that, from a fatigue-management point of view, HRC might not be the ideal method to use in-season with team-sports athletes.

Importantly, to date, studies investigating the acute effects of HRC have only compared this protocol with traditional strength training (34, 38, 66) or other HRC workout performed in hypoxic conditions (64). Thus, there is no current evidence as to whether a circuit training comprising the same exercises of the HRC but performed in an explosive manner using moderate loads (e.g., Power Circuit Training - PCT) also yields high fatigue levels. This is an interesting question given the benefits of utilizing circuit-based training in terms of cardiovascular adaptations and time efficiency (62). PCT could potentially be a method to be used in-season to target power and cardiorespiratory adaptations while, on the other hand, increments in strength could be obtained by using alternative, less demanding and stress-inducing resistance training methods. In team-sports, an important concept concerning strength and power development is that, sometimes, the best or most effective stimulus is not necessarily the most appropriate due to, amongst other factors, the acute fatigue responses.

Accordingly, other training regimens aimed at developing strength and power have long been used by practitioners. Weightlifting movements-based training (67, 68), velocity-based training (36, 69) light or optimal load training (OLT) (44, 70, 71), combination training using high and low loads such as contrast (72) or complex training (CT) (73-75) are examples of such methodologies. Utilizing one over another will depend on the level and training background of the athlete, his/her responsiveness to a specific resistance training program, the type of sport modality, the moment of the season and the demands of competition (54). Remarkably, amongst the referred training methods, two are becoming increasingly popular within the S&C and scientific communities: CT and OLT.

CT consists on coupling biomechanically similar heavy load resistance training exercises (termed conditioning activity (CA)) with plyometric/ballistic or power exercises, set for set, in the same workout (76). It is believed that the CA increases motoneuron excitability and reflex potentiation, thus possibly creating optimal training conditions for subsequent neuromuscular power gains (76). The ability to generate maximal power depends greatly on the ability of the nervous system to activate the muscles involved with the adequate order and magnitude of activation (49).

Theoretically, CT improves performance due to the enhancement of the muscle's explosive capability after being subjected to maximal or near maximal contractions, in a response known as postactivation potentiation (PAP) (77-79). This phenomenon may lead to acute increases in force and power production and has been proposed to occur due to different mechanisms (77). The first is the phosphorylation of myosin regulatory light chain associated with the increase in calcium ion concentration that results in changes in the crossbridges kinetics of the contractile filaments (77). Regulatory light chain phosphorylation is thought to alter the structure of the myosin head making the actin-myosin interaction more sensitive to calcium, hence potentiating subsequent muscle contraction (77). The second mechanism proposed is the recruitment of higher order motor units that occurs after maximal muscle contractile activity (76, 77, 80). Increases in H-wave amplitude, recorded with electromyography, have been found after maximal or near maximal contractions which is believed to be the result of enhanced high order motoneuron recruitment at the spinal cord level (77).

A recent meta-analysis (78) on the factors modulating PAP in jumping, sprinting and throwing tasks concluded that performing a CA produces small PAP on jump and moderate on sprint. Furthermore, it seems that the magnitude of the PAP response depends on the athlete's strength level, the load and type of CA and the rest interval between the CA and the subsequent exercise (78). All these variables may affect the net balance between fatigue and potentiation that always co-exist after the completion of a CA (77, 81), as it can be observed in Figure 2, extracted from Tillin and Bishop (77).

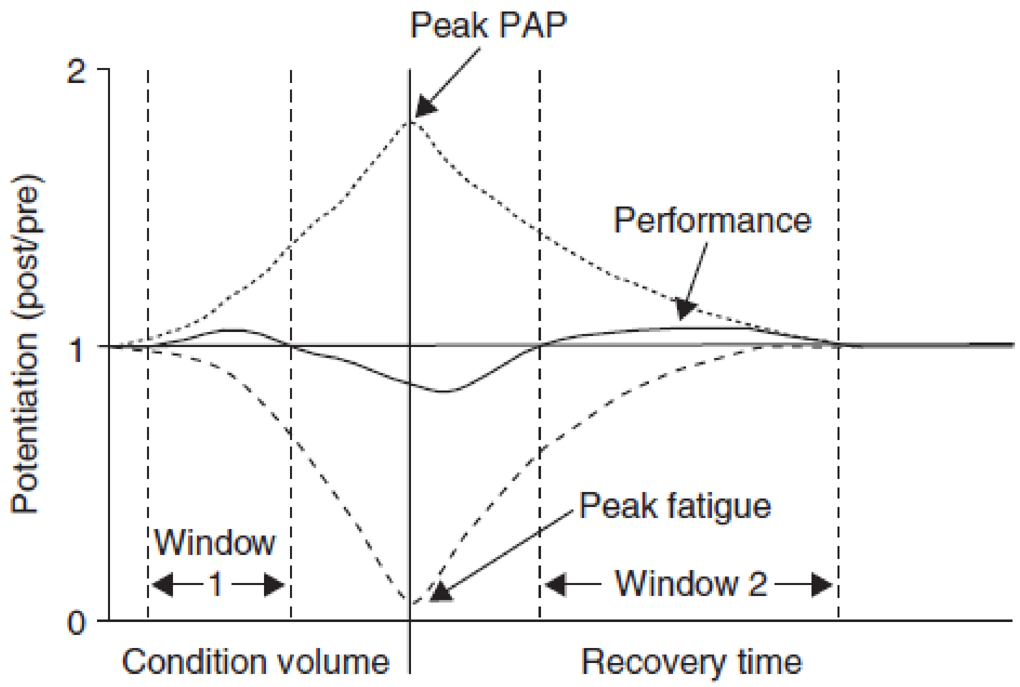

Figure 2. Theoretical relationship between postactivation potentiation and fatigue following a conditioning activity, from Tillin and Bishop (77).

Briefly, the hypothetical relationship represented above indicates that, following a CA, performance may: (I) improve, if potentiation dominates and fatigue is reduced; (II) remain unaltered, if potentiation and fatigue are of similar magnitudes or (III) decrease, if fatigue dominates (77, 78). Notably, there are two potential "windows" during which performance may acutely improve (Figure 2). On the one hand, window 1 is thought to occur when CA volumes are low and PAP responses immediately dominate fatigue. On the other, window 2 is believed to be associated with higher CA volumes that cause fatigue to be dominant on the initial stages post-CA but to dissipate at a faster rate than PAP, allowing a potentiation of subsequent performance to be achieved at some point during the recovery period (77). As several factors seem to play a role in the potentiation phenomenon, PAP and, consequently, CT responses are considered to be highly individualized (78, 79, 82).

Despite the first reports on the application of CT by Verkhoshansky and Tatyan dating back to the year 1973 (83), presently, there is still no consensus on the literature as to its effectiveness. On the one hand, some acute studies (mainly focusing on identifying if PAP was present after the CA and if performance increased subsequently) indicate that CT may indeed result in acute increments in power production (84-88). On the other, there are also several investigations reporting that this type of program does not seem to acutely elicit significantly higher performances (89-93).

Regarding short- and long-term adaptations to CT protocols, only a limited number of studies have investigated the effects of such interventions in team-sports and results are far from being conclusive. For instance, there are studies that found increases in sprint performance in soccer players (94, 95) while others found no positive effects on this variable with athletes from the same sport (70, 96). Similarly, there is evidence supporting that CT may be an effective method to increase VJ height (70, 97) but also studies in which jump performance did not improve with this training regimen (75, 95). Therefore, it remains controversial as to whether CT interventions have a positive effect on athletic performance in team-sports players and further research on this topic is warranted.

Curiously, a survey conducted with NBA S&C coaches about their practices highlighted that CT was the most used method to incorporate plyometric exercises in a workout (15). Twelve out of 20 coaches (60%) reported using it whereas only 9/20 (45%) stated using plyometric on a separate day or before resistance training exercises. On such premise, it is surprising the paucity of research on this training method, particularly in basketball. It remains unclear if CT is more effective than other training programs designed to improve strength and power in basketball players as the few studies conducted with this aim presented contradicting results and used a sample of soccer players (70, 94, 98, 99). Additionally, to author's knowledge, there are no current evidence-based guidelines specific for team-sports on how CT protocols should be employed in terms of the intensity of the CA, training frequency, intracomplex rest intervals (ICRI) or duration of intervention. Thus, it is necessary to systematically review the literature to try to identify possible moderating factors that explain the positive adaptations following CT, keeping in mind, nevertheless, that research has shown that responses to CT are highly individualized and may not equally benefit all athletes in a team (100, 101).

With regards to the other training method previously highlighted in the present document, the OLT may be an alternative to develop strength and power in-season and consists on performing a given exercise with the load that maximizes its mechanical power (49, 102-104). As defined by Knuttgen et al. (105), mechanical power equals force applied multiplied by the velocity of the movement and, thus, is a function of strength and speed of movement. It is worth noting that power and RFD are considered the most important manifestations of strength in sport due to the limited time available to apply force in the majority of sport-specific skills (46, 49, 54, 103, 106, 107), and that developing these qualities has long been one of the most important goals of S&C coaches and sport scientists.

From a theoretical point of view, utilizing the optimal load may result in greater increases in power production because this training method emphasizes both components of the power equation (i.e., force and velocity) (44, 49, 103, 108). The optimal load is the load that allows achieving the greatest peak power on a given exercise, coinciding with the maximum point of the parabolic function obtained from the force-velocity-power relationship, as depicted in Figure 3, retrieved from Haff and Nimphius (106).

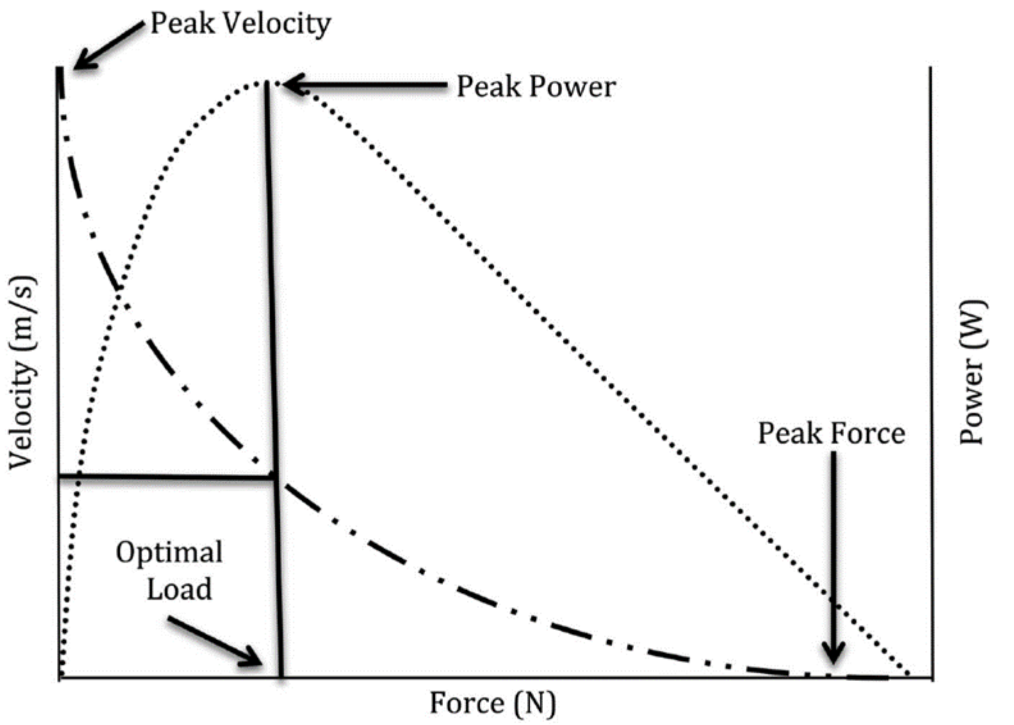

Figure 3. Force-velocity, force-power, velocity-power, and optimal load relationship, from Haff and Nimphius (106).

As it can be observed, maximal power is usually attained at moderate loads, where there is a balance between force and velocity (46, 49, 102). Greater resistances than those considerably reduce the contractile speed and, consequently, the velocity component of the power equation and lighter resistances may not allow for high levels of force to be applied (46, 49). In both cases, power production decreases. A classic study by Cormie et al. (104) empirically demonstrated the previous notion. The power output obtained against loads of 0%, 12%, 27%, 42%, 56%, 71% and 85% of 1RM in the squat exercise was determined, and results indicated that the peak value was reached in the 56% of 1RM condition.

Of note, the optimal load is usually determined as a percentage of the 1RM but can also be presented as a percentage of body mass (44, 102, 109) or based on barbell velocity (110). However, irrespective of the method used to determine the load that maximizes power output, the most important consideration is that this load is exercise-specific and that the same relative intensity cannot be applied to all exercises (49, 102, 104, 111, 112). The biomechanical and neurophysiological characteristics of each exercise influence power production (102, 104). In addition, the optimal load depends on the athlete's training background, individual muscle mechanics, cross-sectional area and fiber type composition (111). Consequently, the optimal load must be individually determined for each athlete and exercise to ensure that the load being used is the one that truly maximizes power output.

Interventions using OLT in team-sports have yield promising results. For example, McBride et al. (113) found that a group of athletes exercising with maximal power loads (i.e., 30% of 1RM in the jump squat exercise) obtained similar strength gains than a group exercising with heavy loads (i.e., 80% of 1RM) but greater improvements in sprint and VJ performance. Furthermore, OLT has also been found to result in slightly superior strength, sprint, VJ and COD ability adaptations in professional soccer players in-season (44) or collegiate volleyball athletes off-season (71) when compared to traditional strength-power training protocols (i.e., a strength block followed by a power block). Therefore, it appears that OLT is an adequate method to improve strength, power and neuromuscular performance of high-level team-sports athletes during both the in-season and off-season periods, without the use of heavy loads. Once again, from a fatigue-management perspective, OLT may potentially be beneficial. However, to date, no study has investigated the effectiveness of this method on basketball players nor has compared it to other training regimens widely used by S&C professionals on this sport as, for example, CT.

In summary, based on the previously exposed, the different training methods presented herein appear to be suitable options to be used with basketball players but further understanding on the specific acute fatigue responses and short-term adaptations is still necessary to help S&C coaches design the most appropriate strength and power-oriented programs, according to the moment of the season. Hence, the present thesis aims to examine the acute effects of different circuit training protocols (i.e., HRC and PCT) on physical and technical performance of basketballers and investigate to what extent these can be utilized during the in-season period, from a fatigue-management approach. In addition, it aims to systematically review the literature in order to determine the effectiveness and the most appropriate intervention characteristics of a commonly used strength-power training method such as CT. Finally, it intends to compare the effects of this specific protocol to other power-oriented training method (i.e., OLT) on neuromuscular performance of basketball players.

II - HYPOTHESES

II. HYPOTHESES

2.1. General hypotheses

An overview of the current state of the literature reveals that resistance training is fundamental for team-sports athletes, from both a performance and injury prevention perspective. However, further research is warranted to ascertain the most appropriate strength and power-oriented protocols to be used during the competitive and more congested period the season, particularly in basketball. In this respect, from a fatigue-management standpoint and based on data from previous investigations, it was hypothesized that a HRC protocol performed with heavy loads would result in higher acute physical and technical performance decrements than a power-oriented circuit training (i.e., PCT) in basketball players, questioning its applicability in-season. Consequently, it was also hypothesized that other training protocols such as CT and OLT would be effective alternatives to apply with team-sports athletes, namely basketball players, to increase strength and neuromuscular performance during the competitive phase of the season.

2.2. Specific hypotheses

The specific hypotheses outlined for each of the studies included in the present thesis are presented below:

Study 1:

- HRC, but not PCT, results in acute vertical and horizontal jump performance impairments in semi-professional basketball players.
- HRC, but not PCT, results in acute declines in repeated sprint and COD ability in semi-professional basketballers.
- HRC, but not PCT, leads to acute decreases in semi-professional basketball players' 3-point shooting accuracy.

- HRC, but not PCT, negatively affects acute upper-body power production in semi-professional basketballers.

- HRC is perceived as more intense than PCT.

Study 2:

- CT is an effective method to improve sprint and VJ performance in team-sports athletes.

- The intensity of the CA, the duration of intervention and the ICRI are moderating factors explaining positive adaptations in sprint and VJ performance following CT programs in team-sports.

Study 3:

- OLT and CT interventions improve vertical and horizontal jump performance, sprint and COD ability in semi-professional basketball players, in-season.

- OLT and CT produce upper- and lower-body maximal dynamic strength gains in basketballers' during the competitive phase of the season.

- OLT and CT intervention do not affect basketball players' body composition during the competitive phase of the season.

- A 6-week, in-season, CT program produces greater maximal dynamic strength gains but similar adaptations on vertical and horizontal jump performance, sprint and COD ability in basketballers when compared to OLT.

III - OBJECTIVES

III. OBJECTIVES

3.1. General objectives

Considering the hypotheses previously outlined, and within the general objectives of this thesis, the present compendium of articles aims to investigate the acute effects of two different resistance circuit training protocols (i.e., HRC and PCT) on semi-professional basketball players' physical and technical performance and perceived exertion, in order to determine to what extent these can be prescribed during the in-season period, from a fatigue-management perspective. Moreover, it aims to systematically review the state of the literature with regards to the effectiveness of CT interventions in team-sports athletes. Lastly, it aims to determine and compare the effects of CT and OLT (i.e., two strength and power-oriented resistance training methods) on neuromuscular performance of basketball players, during the competitive phase of the season.

3.2. Specific objectives

The specific objectives outlined for each of the studies included in the present thesis are presented below:

Study 1:

- To examine the acute effects of a session of HRC and PCT on vertical and horizontal jump performance in semi-professional basketball players.
- To analyze the acute effects of a bout of HRC and PCT on repeated sprint ability (RSA) and COD.
- To investigate the acute effects of a session of HRC and PCT on semi-professional basketball players' 3-point shooting accuracy.
- To investigate the acute effects of a session of HRC and PCT on upper-body power production in semi-professional basketballers.
- To analyze the RPE after each protocol in semi-professional basketball players.

Study 2:

- To systematically review the literature and perform a meta-analysis on the short-term effects of CT interventions in sprint and VJ performance in team-sports athletes.

- To identify possible moderating factors contributing to positive adaptations in sprint and VJ performance following CT programs in team-sports.

Study 3:

- To investigate the effects of OLT and CT on vertical and horizontal jump performance, sprint and COD ability in semi-professional basketball players, in-season.

- To examine the effects of both protocols in basketballers' upper- and lower-body maximal dynamic strength.

- To investigate the effects of OLT and CT on basketball players' body composition.

- To compare the effects of the two protocols on the abovementioned variables after a 6-week intervention, during the competitive phase of the season.

IV – GENERAL OVERVIEW OF THE STUDIES

IV. GENERAL OVERVIEW OF THE STUDIES

STUDY Nº 1:

ACUTE EFFECTS OF TWO DIFFERENT RESISTANCE CIRCUIT TRAINING PROTOCOLS ON PERFORMANCE AND PERCEIVED EXERTION IN SEMI-PROFESSIONAL BASKETBALL PLAYERS

Abstract

This study aimed to investigate the acute effects of two different resistance circuit training protocols on basketball players' physical and technical performance and RPE. In a repeated-measures, crossover experimental design, 9 semi-professional basketball players performed a PCT (45% 1RM) and a HRC (6RM), on consecutive weeks. Vertical and horizontal jump performance, 3-point shooting accuracy, RSA, agility, and upper-body power output were measured before and after training. The RPE was assessed 20 min after the resistance training. One-way repeated-measures analysis of variance showed performance decrements in VJ height and peak power, horizontal jump distance, 3-point percentage, bench press power output, RSA total and ideal time, and COD T-test total time following HRC, but not PCT ($p \leq 0.05$). The RPE was higher in HRC compared with PCT. The results of this study indicated that HRC was perceived as being harder and produced higher fatigue levels which, in turn, lowered acute performance. However, low-to-moderate intensity loads did not negatively affect performance. Thus, completing a PCT session may be the most appropriate option before a practice or game as it avoids acute resistance training-induced performance decrements. However, if the objective of the basketball session is to develop or perfect technical skills during fatiguing conditions, HRC may be the more suitable option.

STUDY Nº 2:

SHORT-TERM ADAPTATIONS FOLLOWING COMPLEX TRAINING IN TEAM-SPORTS: A META-ANALYSIS

Abstract

The purpose of this meta-analysis was to study the short-term adaptations on sprint and VJ performance following CT in team-sports. CT is a resistance training method aimed at developing both strength and power, which has a direct effect on sprint and VJ. It consists on alternating heavy resistance training exercises with plyometric/power ones, set for set, on the same workout.

A search of electronic databases up to July 2016 (PubMed-MEDLINE, SPORTDiscus, Web of Knowledge) was conducted. Inclusion criteria: (I) at least one CT intervention group; (II) training protocols ≥ 4 weeks; (III) sample of team-sports players; (IV) sprint or VJ as an outcome variable. Effect sizes (ES) of each intervention were calculated and subgroup analyses were performed.

A total of 9 studies (13 CT groups) met the inclusion criteria. Medium ES (ES = 0.73) were obtained for pre-post improvements in sprint, and small (ES = 0.41) in VJ, following CT. Experimental-groups presented better post-intervention sprint (ES = 1.01) and VJ (ES = 0.63) performance than control-groups.

Regarding sprint, large ESs were exhibited in younger athletes (< 20 years old; ES = 1.13); longer CT interventions (≥ 6 weeks; ES = 0.95); CA with intensities ≤ 85% 1RM (ES = 0.96) and protocols with frequencies of < 3 sessions/week (ES = 0.84). Medium ESs were obtained in Division I players (ES = 0.76); training programs > 12 total sessions (ES = 0.74).

Concerning VJ, large ESs were displayed in programs with > 12 total sessions (ES = 0.81). Medium ESs obtained for under-Division I individuals (ES = 0.56); protocols with ICRIs ≥ 2 min (ES = 0.55); CA with intensities ≤ 85% 1RM (ES = 0.64); basketball/volleyball players (ES = 0.55). Small ESs were found for younger athletes (ES = 0.42); interventions ≥ 6 weeks (ES = 0.45).

In conclusion, CT interventions have positive medium effects on sprint performance and small effects on VJ in team-sports athletes. This training method is a suitable option to include in the season planning.

STUDY Nº 3:

SHORT-TERM OPTIMAL LOAD TRAINING VS A MODIFIED COMPLEX TRAINING IN SEMI-PROFESSIONAL BASKETBALL PLAYERS.

Abstract

This study investigated the effects on neuromuscular performance of a 6-week OLT and a novel Modified Complex Training (MCT) (complex pairs: the same exercise using a moderate and an OL) in basketball players, in-season. Eighteen male athletes were randomly assigned to one of the protocols. Anthropometric measurements were taken to evaluate body composition. Lower- and upper-body maximum dynamic strength, countermovement jump (CMJ), standing long jump (SLJ), 10 m sprint and COD were also assessed. Moderate-to-large strength gains (presented as percentage change ±90% confidence limits) were obtained for half-squat (OLT: 10.8 ±5.3%; MCT: 17.2 ±11.6%) and hip thrust (OLT: 23.46 ±17.7%; MCT: 28.2 ±19.0%). OLT athletes achieved likely small improvements in sprint (1.6 ±1.6%) and COD (3.0 ±3.2%). Players in the MCT attained likely moderate improvements in COD (3.0 ±2.01%) and possibly small in SLJ (2.5 ±4.6%). No protocol relevantly affected CMJ or body composition. An ANCOVA test revealed unclear between-group differences. In conclusion, both protocols increased basketball players' strength without the use of heavy loads (> 85% 1RM) and without impairing sprint, CMJ and SLJ performance. These findings suggest that basketball S&C professionals may use either method to counteract strength losses during the season.

V – STUDY 1

V. STUDY 1:

ACUTE EFFECTS OF TWO DIFFERENT RESISTANCE CIRCUIT TRAINING PROTOCOLS ON PERFORMANCE AND PERCEIVED EXERTION IN SEMI-PROFESSIONAL BASKETBALL PLAYERS

5.1. INTRODUCTION

Basketball is a sport characterized by its intermittent, high-intensity activity that requires players to perform actions such as: jumping, sprinting, shuffling or changing directions (1, 2). Increased VJ ability (9, 10), RSA (11, 114), agility and COD (9, 10) are important determinants of high performance in basketball. Hence, S&C is a vital component in this sport and it focuses on enhancing aerobic capacity, agility, COD ability, speed, strength and power (15). In fact, the ability to generate power and explosive force is essential for athletic performance (46).

Overall, both heavy resistance training and power training using light-to-moderate loads are executed to improve athletic performance in team-sports during the season (15, 43, 115). On the one hand, heavy resistance training increases maximal strength (46), which is considered the physical quality that most affects maximal power (49). On the other hand, power training not only increases maximal power outputs using lighter loads and maximal movement velocities, but also triggers specific neuromuscular adaptations that result in performance enhancements (46, 49, 113). The total work, the duration of activation and fatigue levels with power training are generally lower compared to heavy resistance training (116).

Fatigue following resistance training has been widely studied (35, 116, 117). Fatigue is a complex, task dependent phenomenon (30) that is defined as an exercise-induced reduction in the ability to exert muscle force or power (29) or, more globally, as an exercise-induced decline in neuromuscular performance (28). It may occur due to changes at the muscular level (peripheral fatigue), as well as to central nervous system failure to adequately drive the motor neurons (central fatigue) (29, 30). With regards to neuromuscular performance, time increments in sprint, agility, COD or RSA tests could be interpreted as manifestations of fatigue. In addition, fatigue may also manifest itself as a decrement in the technical execution or in the motor skill outcome, which can be measured as ball velocity or accuracy (28, 40).

Understanding the acute effects of post-resistance training fatigue on basketball players' performance is crucial since, during the competitive season, moderate and high-intensity resistance training sessions are performed (15, 16). To our knowledge, only one study (118) has investigated the acute effects of strength training in basketball players' performance by analyzing VJ, anaerobic power and shooting accuracy following a moderate intensity resistance training. Results obtained indicated that such training, when completed 6h before a basketball practice, had no negative effects on performance. However, some semi-professional teams or teams that must travel regularly between games may not have the opportunity to perform strength training in the morning and a basketball practice in the afternoon. Therefore, these two training components are generally executed in sequence. Nonetheless, there exists a lack of research addressing the acute effects that strength/power training may have on players' specific physical and technical performance due to post-resistance training fatigue. In fact, no research has been conducted with heavy resistance and power training completed immediately before a regular basketball practice and, for that reason, their effects on basketballers are still unknown.

Therefore, the main aim of this study was to investigate the acute effects of two different resistance training protocols on the main factors of high performance in basketball. We hypothesized that power training would result in less perceived exertion than heavy resistance training and would also result in lower declines on performance on vertical and horizontal jumps, shooting accuracy, COD, RSA and upper-body power output. Results may have important implications when determining the objective of the on-court basketball practice if a strength session is performed immediately before.

5.2. METHODS

5.2.1. Study design

A repeated-measures, crossover, experimental design was used. The practical experiment was conducted after the end of the competitive season 2013/2014, in which participants played a total amount of 37 games (30 official and 7 pre-season) and trained over 330h (250h of basketball practice and 80h on strength sessions). Procedures lasted 3 weeks, with participants being tested once every week. On week 0, on the same day, all participants were tested on resting conditions (REST) and completed a familiarization set of the resistance training protocols. They were then randomly divided in 2 groups (G1 n = 4, G2 n = 5) so that it was possible to properly monitor the strength training and testing procedures. On week 1 and week 2 subjects performed the two different resistance training protocols - HRC (60) and PCT - always followed by the same testing procedures performed on week 0. G1 executed the HRC on week 1 and PCT on week 2. G2 completed the PCT on week 1 and HRC on week 2. For each group, resistance training and testing were performed on the same day of the week at the same hour of the day.

5.2.2. Participants

Nine semi-professional male basketball players (Table 1) competing in Spanish League EBA (4th Division), with at least 5 years of playing experience and 1-year involvement in resistance training, volunteered to participate in the study. None of them had a previous history of injury, diseases or was taking medications during the study. Players were fully informed about all testing and training procedures and signed a written informed consent. Before the study, all of them underwent a physical examination by the team physician and were cleared of any endocrine disorder that might confound or limit their ability. Approval for the study was given by the Human Subjects Ethics Committee of the San Antonio Catholic University of Murcia, Spain, in accordance with the 2008 Helsinki Declaration. Participants were instructed to maintain their normal diet habits and team´s regular practice schedule of 4 basketball training sessions per week throughout the investigation period.

Table 1 - General characteristics of the participants (n=9)

Age (years)	Height (cm)	Body Mass (kg)	BMI (kg/m²)	Half-Squat 1RM (kg)	Bench Press 1RM (kg)
21.44 ± 2.5	197.69 ± 8.38	93.19 ± 14.46	23.77 ± 12.93	157.44 ± 21.98	85.82 ± 20.26

BMI = body mass index; 1RM = 1 repetition maximum.

5.2.3. Testing procedures

All testing measurements were completed in the UCAM Research Center for High Performance Sports (Murcia, Spain) at the end of the competitive season. Procedures were carried out after 36h of rest, during the recovery microcycle, to limit differences in training status and/or intensity (119). Participants were tested in 3 separate occasions: (I) on REST, the week prior to the beginning of the training protocols; (II) immediately following the HRC training session and (III) immediately following the PCT training session. On week 0, the first day of testing, participants completed a standard warm-up of 5 min light jogging on the treadmill followed by the joint mobility exercises and dynamic stretching routine the team executed in their regular basketball practices. No static stretching was performed prior to testing (120). On this day, after all tests were concluded, the 6RM load for all exercises was determined. An initial resistance was selected based on the subject's perceived capacity to move the load only 6 times. After the first set, if ± 1 repetition was completed, the load was adjusted by approximately 2% and if subjects were able to lift ± 2 repetitions, accommodated by 5%.

The testing sequence lasted 34 min for each player and consisted of a 3-point shooting test, horizontal and VJ tests, COD test, RSA test and bench press power output test. Players were familiar with all the testing procedures as they had performed them during the season. The order of the tests was kept the same in all 3 sessions and each assessment was conducted by the same investigator in every occasion. The same certified S&C coach (NSCA-CSCS) supervised all the testing and training procedures.

5.2.3.1. 3-point shooting test

The shooting test performed was the one described by Pojskić et al. (121) for 3-point shooting without fatigue. Each player performed 2 jump shots behind the 3-point line from 5 different positions, on a total of 10 shots per series. The positions were determined with marks on the floor so that the players shot from the exact same place on every series. A total of 3 series were completed, but only the last 2 were considered for analysis, since the first was a warm-up. Each testing series was separated by 2 min. The selected test has been considered as a valid and reliable instrument to measure basketball 3-point shooting accuracy (121) and was performed 3 min after the end of the resistance training protocols.

5.2.3.2. Horizontal jump test – Standing long jump

The SLJ was performed with participants starting before a line drawn on the floor, feet pointing forward placed shoulder width, and then jumping as far as possible, landing on two feet. Arm-swing and a countermovement were allowed (122). Participants performed two practice trials and then two test trials separated by 1 min rest. The distance, measured to the nearest 0.01 m, was considered as the horizontal displacement of the feet between the starting line and the point where the back heel contacted the floor. Only the best result was considered for analysis. The test was performed 8 min post-resistance training.

5.2.3.3. Vertical jump test – Countermovement jump

The CMJ was performed on a Kistler 9286BA portable force platform (Kistler Group, Winterthur, Switzerland). Players started in a standing position with feet placed shoulder width, on the center of the force platform, and were asked to jump as high as possible with a rapid countermovement. Hands were kept on the hips throughout the execution of the jump. The depth of the countermovement was self-selected and subjects were asked to try and land close to the point of take-off (122). Participants executed two submaximal trials to ensure proper execution of the jump and then performed two maximal CMJ on the force platform with 1 min rest between them. Only the best attempt was considered. The parameters calculated were: (I) jump height, based on the velocity at take-off; (II) absolute peak power and relative peak power, calculated with Microsoft Excel software (Microsoft Corporation, Redmond, WA, USA) from the data exported from the force platform. CMJ has been considered the most reliable and valid test for the estimation of explosive power of the lower limbs (122). It was executed 10 min after the end of strength training.

5.2.3.4. Change of direction test – T-test

The T-test was performed using the standard protocol (123). At the tester's signal, players sprinted 9.14 m forward to a first cone and touched it. Then, subjects shuffled 4.57 m to the left and touched a second cone. After that, they shuffled 9.14 m to the right and touched a third cone and then 4.57 m to the left, back to point where the first cone was, touching it again. Finally, participants back-peddled 9.14 m, passing through the finish line. Time was measured with wireless photocells from Microgate's WITTY System (Mircrogate, Bolzano, Italy) placed on the starting line. Time started counting once the players broke the light beam a first time and stopped when they broke it a second time. Participants were verbally encouraged throughout the test and were asked to perform a maximal effort. The only parameter considered was total time. Two trials were allowed on each testing session, separated by 2 min. Only the best time was considered. The T-test is a reliable and valid instrument (123) and was performed 17 min after the end of the resistance circuit protocols.

5.2.3.5. Repeated sprint ability test

The RSA protocol used was the one proposed by Castagna et al. (12) and consisted of 10 shuttle-run sprints of 30 m (15 + 15 m) with 30 s rest between each bout. An excellent reliability and validity of this basketball-specific test has been reported (12). Wireless photocells from Microgate's WITTY System (Mircrogate, Bolzano, Italy) were placed in the starting line to record the time of each sprint. Participants were asked to perform a maximal effort and verbal encouragement was given throughout the test. The parameters calculated were: (I) total time, consisting of the sum of all 10 sprint times; (II) ideal time, calculated as the best sprint time multiplied by 10; and (III) performance decrement (PDec) (%), determined according to the equation proposed by Fitzsimons et al. (124):

PDec = 100* (Total Sprint Time/Ideal Sprint Time) – 100.

The RSA test was performed 23 min after the end of the strength training.

5.2.3.6. Bench press power output test

The bench press power output test was conducted on a modified Smith machine with a linear encoder (Chronojump-BoscoSystem, Spain) attached to the barbell and interfaced with a computer. All data was recorded with Chronojump-BoscoSystem software. The test was completed with each participant's bench press 6RM load, previously determined. Participants completed three repetitions descending the barbell to the point where it nearly touched the chest and were verbally encouraged throughout the exercise to move the barbell as fast as possible in the concentric phase. Peak power was measured and only the best repetition was considered. A spotter was used during the test to assist in racking the resistance and to ensure safety and proper range of motion. This test was performed 33 min after each resistance circuit training was completed.

5.2.3.7. Rating of perceived exertion – Borg CR-10 scale

RPE was assessed on week 1 and week 2 using the Borg CR-10 scale (125). Participants were instructed on how to use the scale before the start of the resistance training, on week 1. They were shown the RPE table to clearly understand what each number represented. Approximately 20 min after both HRC and PCT and before performing the RSA test, participants were asked "*How was your workout*?" and presented with the table. This time frame was selected so that difficult or easy elements performed close to the end of the session would not tilt the RPE of the entire bout (126).

5.2.4. Training protocols

The HRC protocol was based on the one proposed by Alcaraz, et al. (60). It consisted of 6 exercises, divided in two blocks of 3 (Figure 1). Participants completed 4 sets of each block with the previously determined 6RM load for every exercise. The local recovery, for each muscle, was 3 min (i.e., time separating one set of a given exercise and the next set of same exercise) and 40 s was the rest period between consecutive exercises. The training session started with a warm-up consisting of 5 min of light jogging on the treadmill followed by joint mobility exercises and dynamic stretching. Specific warm-up consisted of 1 set of 10 repetitions of each exercise of the first block with 50% of the 6RM load. The second block started 5 min after the end of the block 1. The first 3 min between the two blocks consisted on a passive rest period and the final 2 min were destined to the specific warm-up of the second block. Upper- and lower-body muscle groups were alternated in consecutive exercises in order to allow local recovery to occur. Rest intervals shorter than 3 min for the same exercise don´t allow participants to maintain the number of repetitions at the same intensity (127).

Players were verbally encouraged to execute the concentric phase of all exercises at the maximum possible velocity and lifted weights that allowed only 6 repetitions to be performed. If necessary, during the workout, the 6RM loads were adjusted for every set by 2% if a participant performed ± 1 repetition, or by 5% if he completed ± 2 repetitions.

The PCT protocol was very similar to the HRC. The training consisted of the same 6 exercises divided in the same two blocks (Figure 1). The warm-up protocol was identical as were the duration of the rest periods between exercises, the local recovery and the number of sets and repetitions performed. The main differences between the PCT and HRC protocols were on the loads lifted, on the velocity of execution of the exercises and whether these were performed to volational fatigue or not. The PCT protocol was executed with the loads corresponding to maximal power output in the half-squat in basketball players, 45% of 1RM (128), and volational fatigue was not achieved. The 1RM load was estimated using the Brzycki equation, previously considered a valid method (129).

Given that the loads were considerably lower, the velocity on the execution of the exercises was higher than on HRC. Participants were verbally encouraged to execute the concentric phase at the maximum possible velocity. For safety reasons, they were not allowed to jump on the half-squat or to lose contact with the barbell on the bench press.

In both training protocols the concentric:eccencentric ratio was the same, 1:3. Spotters were present in every station of the circuit to ensure safety to the participants and to control the rest periods. The duration of the HRC and PCT sessions was 45 min.

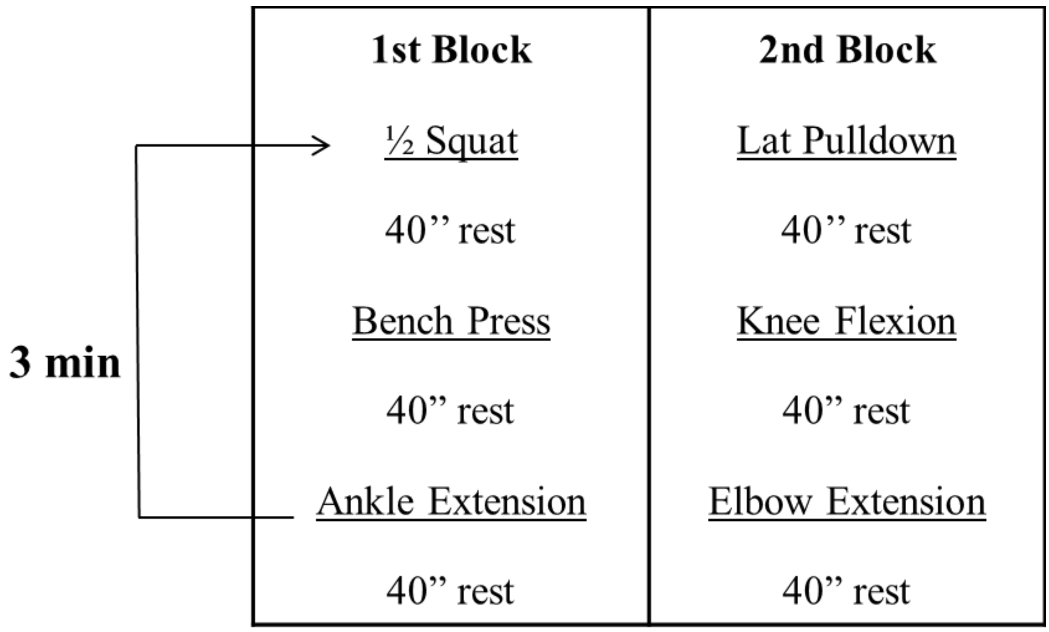

Figure 1. Resistance training protocol for both HRC and PCT. The exercises performed, the exercise order, the rest period between exercises and local recovery time were all kept the same in both training conditions. The sole difference between HRC and PCT regarded training intensity and working loads.

5.2.5. Statistical analysis

Statistical analysis was conducted using IBM SPSS Statistics 21.0 for Windows (IBM SPSS Inc., Chigaco, IL, USA). All the data were expressed as mean ± standard deviation (SD). Normality was assessed with a Shapiro-Wilk test and homogeneity of variances with a Levene test. Parametric tests were applied. ANOVA repeated-measures analysis of variance, with intervention (training protocol) as factor, was performed to examine within-subject differences among REST, HRC and PCT. Bonferroni adjustment of confidence interval for multiple comparisons was used to locate the pairwise differences between the means. Power (1-β) was determined for all variables and ES were calculated using Cohen's d. Statistical significance was considered for $p \leq 0.05$.

5.3. RESULTS

5.3.1. Vertical and horizontal jumps

CMJ height (1-β = 0.87; ES = 0.61), absolute (1-β = 0.96; ES = 0.73) and relative peak power (1-β = 0.95; ES = 0.72) values and SLJ horizontal distance (1-β = 1.00; ES = 0.89) were determined in all testing conditions (Table 2). HRC protocol provoked a significant decrement ($p \leq 0.05$) in all variables studied. These declines were significantly greater ($p \leq 0.05$) when compared to PCT. No statistical significance was found between PCT and REST values.

5.3.2. Shooting

On the 3-point shooting test the parameters calculated were the total number of shots made (1-β = 0.99; ES = 0.74), number of shots made per series (1-β = 0.989; ES = 0.74) and shooting percentage (1-β = 0.99; ES = 0.74) (Table 2). After the completion of the HRC training the shooting accuracy was significantly lower (p ≤ 0.05) when compared to the other two testing conditions. No statistical significance was found between PCT and REST values.

Table 2 - Performance measurements for all variables on the three experimental conditions

	REST	**HRC**	**PCT**
CMJ			
Height (m)	0.35 ± 0.07	0.28 ± 0.08*	0.33 ± 0.07†
Absolute Peak Power (W)	5078.18 ± 436.83	4400.74 ± 430.01*	4819.44 ± 341.55†
Relative Peak Power (W/kg)	55.70 ± 6.52	48.43 ± 7.39*	52.66 ± 7.06†
SLJ			
Distance (m)	2.47 ± 0,25	2.36 ± 0,25*	2.43 ± 0.26†
3-Point Shooting			
Total Shots Made	9.67 ± 1.70	7.78 ± 1.40*	10.56 ± 2.59†
Total Shots Made per Series	4.83 ± 0.85	3.89 ± 0.70*	5.28 ± 1.29†
Total Shooting Percentage (%)	48.33 ± 8.50	38.89 ± 6.98*	52.78 ± 12.93†
Repeated Sprint Ability			
Total Time (s)	57.50 ± 2.89	59.24 ± 3.32*	58.08 ± 3.33†
Ideal Time (s)	55.88 ± 2.68	56.90 ± 2.82*	56.23 ± 3.02†
Performance Decrement[a] (%)	2.89 ± 0.96	4.22 ± 0.75*	3.29 ± 0.94
T-test			
Total Time (s)	9.52 ± 0.63	9.71 ±0.69*	9.54 ± 0.72†
Bench Press			
Power Output (W)	595.40 ± 80.25	518.58 ± 95.32*	574.94 ± 93.57†
Borg CR-10 Scale			
Rating of Perceived Exertion[b] (AU)		7.89 ± 0.57	4.33 ± 0.94†

* $p \leq 0.05$, as related to REST; † $p \leq 0.05$ as related to HRC

[a]Performance Decrement calculated with the following equation (124):

PDec = 100 (Total Sprint Time/Ideal Sprint Time) – 100*

[b]Rating of Perceived Exertion was assessed with Borg CR-10 Scale, 20 min post-training (126).

5.3.3. Repeated sprint ability and change of direction

Values obtained in RSA and T-test are expressed in Table 2. RSA total time (1-β = 0.99; ES = 0.81) was higher ($p \leq 0.05$) following the HRC session, when compared to the PCT session and REST. Concerning RSA ideal time (1-β = 1.00; ES = 0.85), the trend was similar. The slowest performance was found after the HRC training, followed by the PCT and REST. There were significant differences ($p \leq 0.05$) between HRC and REST and between HRC and PCT, but not between REST and PCT. Regarding RSA PDec (1-β = 0.77; ES = 0.54), values were lower on REST than following either of the resistance training protocols. The only significant differences ($p \leq 0.05$) were found between HRC and REST.

On the T-test, results showed that following HRC training, total time (1-β = 1.00; ES = 0.86) was significantly higher ($p \leq 0.05$) than in the other two conditions, indicating a lower performance. No statistical differences were found between PCT and REST.

5.3.4. Bench press power output

Bench press power output (1-β = 0.88; ES = 0.62) values obtained (Table 2) indicated that performance was significantly lower ($p \leq 0.05$) on HRC when compared to both REST and PCT. No statistically significant differences were found between PCT and REST.

5.3.5. Rating of perceived exertion – Borg CR10 scale

RPE (1-β = 1.00; ES = 0.90) (Table 2) was assessed with the Borg CR-10 scale and results showed that participants considered the HRC training as being more intense than the PCT protocol. According to the Borg CR-10 scale, HRC was perceived as "*Very Hard*" and PCT as "*Somewhat Hard*". Differences were statistically significant with $p \leq 0.05$.

5.4. DISCUSSION

To our knowledge, this is the first study that investigated the acute effects of HRC and PCT on basketball-specific physical and technical skill performance. The main findings supported our hypothesis since immediately following a PCT bout CMJ and SLJ performance, shooting accuracy, RSA, COD and upper-body power output were not negatively affected in basketballers. Furthermore, performing a PCT session was perceived as less intense than completing a HRC bout. These findings suggested that power training may be the most appropriate option prior to a practice/game as it avoids acute resistance training-induced performance decrements and because it minimizes fatigue, thus preventing an increased risk of injury (5). However, if the objective of the basketball session is to develop or perfect technical skills under fatiguing conditions, HRC may be the more suitable option.

Previous studies have also demonstrated increased levels of fatigue following high-intensity resistance training (35, 116). Linnamo et al. (116) showed that maximal strength training lead to greater neuromuscular fatigue than power training using 40% 1RM. This is in accordance with the performance decrements observed on all variables measured in our basketballers, following HRC compared to PCT.

Shooting, which is the most important action in basketball, can be affected by fatigue (42, 121). Its accuracy depends on an adequate technique (42) and our results showed that after HRC, the total number of shots made, mean shots made per series and total shooting percentage were significantly lower. The present data support the idea that the magnitude of immediate fatigue and its recovery are dependent on the intensity of the performed task (130). In fact, higher levels of fatigue have been shown to affect motor skills outcome in basketball players (28, 40, 121). This may not be necessarily a negative aspect if the objective of the practice is to perform shooting drills when players are already fatigued, as it occurs in competition. In reality, some teams combine high-intensity strength training with low intensity technical sessions (16) due to time limitations during the competitive season (15). Although basketball shooting kinematics was not analyzed in our study, modifications in the movement pattern most probably occurred, due to fatigue. This phenomenon has been reported in previous research with elite basketball players (42). Another interesting finding is that our data seem to be the first to indicate that basketball-specific motor skills remain unaltered in trained individuals immediately following a moderate intensity strength training session. Kauranen et al. (131) had already reported that motor skill performance of the hand (reaction time, speed of movement, tapping speed and coordination) was not altered immediately after moderate intensity training. However, those results were obtained with untrained subjects.

Other important factors related to success in basketball are the jumping ability and the power output production. Thus, CMJ and SLJ are commonly used to assess basketball players' physical fitness (45). Our data indicated a decline in jump performance following HRC supporting several studies that have shown that fatigue negatively affects VJ performance (117, 132). It is probable that the main mechanisms responsible for the diminished CMJ and SLJ performance were peripheral in origin, given the time elapsed between the end of resistance training and both tests was 10 min (130). Raastad and Hallen (130) suggest that 5 min after exercise cessation, reduced neural activation is practically recovered and, so, central fatigue was not a major factor on decrements in CMJ height. Furthermore, declines in power output in dynamic tasks have been associated to peripheral fatigue, specifically to a reduction on shortening velocity (35). This phenomenon can be related to other of our study's variables as the same mechanisms were responsible for the declines observed in bench press power output after HRC. Even though there are differences in fatigability of upper- and lower-body, declines on power and velocity are believed to be peripheral in origin in both CMJ and bench press (133).

In basketballers, a significant correlation between CMJ and RSA has been reported (114). As previously observed in our study, a decline in CMJ performance occurred following HRC. Hence, RSA could be expected to be affected as well. In effect, concerning this latter variable, performance declined after HRC. Participants were significantly slower completing the whole 10 sprints and also fatigued more throughout the protocol. Although no studies have investigated the effects of resistance training on RSA performance, the decrements observed may be related to the fact that a HRC session was performed. Heavy resistance training leads to a high rate of energy utilization through phosphogen breakdown and activation of glycogenolysis which results in significant decreases in ATP and muscle glycogen concentration (134). In fact, preceding high-intensity efforts may compromise RSA due to limitations in energy supply, mainly from phosphocreatine, and alterations in muscle excitability related with sodium/potassium disturbances at the muscular level (135).

The main energy metabolisms involved in RSA are most likely the same as in the T-test since this latter test consisted of a maximal effort completed, in all three experimental conditions, in less than 10 s. Analyzing the results, we observed increases in total time only after HRC. We consider the causes for performance declines in COD were the same as in the RSA effort. Possible decreased muscle glycogen concentration (28, 134) and post resistance-training impaired muscle contractile function (35) contributed to the results obtained. Meylan et al. (136) state that sudden bursts of power are needed to rapidly change direction during athletic actions and, as our CMJ results showed, lower-body power production was impaired, which possibly contributed to reduce participants' COD ability.

As stated before, our results indicated that fatigue was greater after HRC when compared to PCT. This conclusion was also sustained by the subjects' perception of effort following each protocol. RPE was significantly higher following HRC which is not surprising due to the relationship between RPE and resistance training intensity (126). Day et al. (126) conducted a study in which participants completed, on separate days, the same resistance training protocol with different loads (5RM, 10RM and 15RM) and concluded that lifting heavier loads was perceived as more difficult. Heavy resistance training requires greater muscle tension development that results in an increment of motor unit recruitment and firing frequency, thus increasing the perception of effort (126).

The main methodological limitation of the present study was the small sample size utilized, even though medium to large ES were obtained for all variables. Another limitation was the fact that the last assessment was completed more than 30 min after the end of both resistance protocols since all tests were performed in sequence, in the same session. The long recovery period between some tests and the end of the training could have influenced the results. However, the order of the testing was the same for each participant in all the sessions.

Further studies are needed to determine the fatigue mechanisms that lowered performance as the methodology used did not allow for the determination of such mechanisms. Furthermore, the long-term effects of these two resistance training protocols on the variables studied are still unknown on basketball players.

5.5. CONCLUSIONS AND PRACTICAL APPLICATIONS

The results of the present study may be useful for S&C coaches to plan their sessions more effectively. Our data show that a PCT session may be an appropriate option for basketball players to complete prior to a tactical session/game as it avoids acute resistance training-induced performance decrements. Jumping performance, shooting accuracy, RSA, COD ability and upper-body power output are not negatively affected. On the other hand, post-session performance impairments in the main determinants of success in basketball are present after a HRC session, for at least 30 min. This may lead to a decline in the quality of the practice/game and to an increased risk of injury.

Nonetheless, HRC is important to develop/maintain maximal strength. For this reason, it should be included in the strength program of a basketball team. HRC may be a suitable alternative when the objective of the on-court practice is to develop/perfect technical skills under fatiguing conditions, as it occurs in competition.

VI – STUDY 2

VI. STUDY 2:

SHORT-TERM ADAPTATIONS FOLLOWING COMPLEX TRAINING IN TEAM-SPORTS: A META-ANALYSIS

6.1. INTRODUCTION

In team-sports, the capacity to maximize neuromuscular power production is fundamental to success and critical to achieve high levels of performance and greater velocities in sport specific movements (49). The improvement of high-intensity, explosive actions such as sprint or VJ is an important goal for coaches and athletes (137, 138). In fact, Faude et al. (139) concluded that straight sprint is the most important action when scoring or assisting a goal in elite football. For the purpose of this meta-analysis, it is important to state that in most team-sports the distances covered in sprint efforts are usually short (1, 140, 141) and consist primarily on accelerations and decelerations without developing full speed (142).

Studies conducted with American football players have shown that Division I players are stronger, faster and more powerful than their Division II or Division III counterparts (143). Also, Cometti et al. (144) reported that elite soccer players displayed higher strength values and 10 m sprint performance when compared to amateurs. This indicates that strength and power production may differentiate athletes from different competition levels. Therefore, due to the association between these variables and higher performance levels in team-sports, investigating about training methods designed to improve strength and neuromuscular power is of great interest.

Research has shown that resistance training performed with heavy loads as well as programs using light or optimal loads, plyometric training and ballistic exercises lead to increments in maximal power outputs (49), VJ (45, 138, 145, 146) and sprint performance (137, 138, 146, 147). Traditional heavy resistance strength training results in increments in maximal strength and power by targeting mainly the force component of the power equation (power = force x velocity) (46, 49). However, this type of loading does not play a relevant role in maximal power improvements after reasonable levels of strength are attained (46, 49). On the contrary, plyometric and ballistic/power exercises performed with lighter loads allow for higher movement velocities to be achieved, which elicits specific adaptations in neural drive that ultimately lead to an increased RFD and maximal power production (46, 49, 146). Finally, methods that combine both strength and power exercises may produce superior improvements in sprint and VJ when compared to strength, power or speed training alone in untrained subjects (145, 148) and athletes (149).

Most recently, CT has emerged as a training method aimed at developing strength and neuromuscular power. It consists on coupling biomechanically similar heavy load resistance exercises (also referred to as CA) with plyometric or power exercises (maximal movement velocities), set for set, in the same workout (76, 80). Two consecutive exercises combined are termed a complex pair (100) (e.g., a half-squat followed by a CMJ). According to Ebben (76), heavy resistance training increases motoneuron excitability and reflex potentiation, thus possibly creating optimal training conditions for subsequent neuromuscular power gains. Furthermore, Cormie et al. (49) state that the ability to generate maximal power depends greatly on the ability of the nervous system to activate the muscles involved with the adequate order and magnitude of activation.

Theoretically, CT improves performance due to the enhancement of the muscle's explosive capability after being subjected to maximal or near maximal contractions, in a response known as PAP (77, 78, 100). The phosphorylation of myosin regulatory light chain (77) and the recruitment of higher order motor units that occurs after maximal muscle contractile activity (77, 150) are the mechanisms believed to contribute to PAP. Seitz and Haff (78) performed a meta-analysis on the factors modulating PAP of jump, sprint, throw and upper-body ballistic performances. According to the authors, performing a CA produces small PAP on jump and moderate on sprint. Furthermore, PAP effects seem to be higher in stronger individuals (squat: body mass ratio ≥ 1.75 for men and > 1.5 for women) and when the CA consists on plyometric drills or resistance exercises ≥ 85% of 1RM. The results also indicated that the greatest PAP response is obtained after longer recovery intervals (≥ 5 min) between the CA and the subsequent exercise and also when multiple sets are performed instead of a single one (78). However, it has also been suggested that CA may have a warm-up effect rather than an actual potentiating one (82) and that this should not be excluded as a possible cause for the improved performance in the subsequent exercise.

CT is considered a time efficient method (92), but there is no clear agreement on its actual effectiveness (151). Several studies (87, 89, 91) investigated its acute effects, mainly focusing on identifying if PAP was present after the CA and if performance increased. Results found were somehow contradicting, since some investigations (86, 87) indicated that CT resulted in subsequent acute increments in power production whereas other studies reported no significantly higher performance gains (89, 91). Factors like training background (87, 151), subjects' strength level (79, 87, 100), ICRI (78, 79, 151) or the load used in the CA (78, 79, 86) have been proposed as influential in the acute response to CT.

Concerning short- and long-term adaptations, few studies have been conducted to assess the efficacy of CT protocols. Research on recreationally trained individuals indicated that CT did not result in higher whole- and lower-body power output increments when compared to compound training (i.e., strength and power sessions on alternate days) (152) or when compared to resistance training only or plyometric training alone (92). Furthermore, maximal strength adaptations were similar in all different training conditions (92, 152). Regarding team-sports athletes, disparities can be found within the results published in the literature. Faude et al. (96) found increases in lower-body maximal strength and VJ height following a CT intervention with soccer players, but no improvements in 10 and 30 m sprint or COD. McMaster et al. (74) reported increases in both maximal strength and sprint ability in rugby players following CT and Alves et al. (95) obtained significant improvements in sprint (5 and 15 m) but not in CMJ or COD performance in soccer players. Other studies reported increases in sprint (88, 94) or VJ (75, 153, 154) performance or no positive adaptations on these variables after a several weeks CT program (73).

It remains controversial as to whether CT has a positive effect on sprint or VJ in team-sports but a recent meta-analytical review on the effects of resistance training in youth athletes concluded that for muscular power development, CT provided a greater magnitude of change compared with other resistance training protocols (155). This suggests that CT may be a promising method to develop neuromuscular power and athletic performance but further understanding on how to organize its training variables is necessary.

Therefore, the main aim of this meta-analysis was to examine the effects of short-term CT interventions (at least 4 weeks) on sprint and VJ performance in team-sports athletes and to identify the possible moderating factors contributing to such adaptations.

6.2. METHODS

6.2.1. Literature research and data sources

This research was completed in accordance with the recommendations of the PRISMA statement (156). The literature research was conducted in different online databases: PubMed MEDLINE, SPORTDiscus and Web of Knowledge (WoS). The search included studies published until July 2016 and the following keywords were introduced, either individually or combined: "complex training", "postactivation potentiation", "performance", "athletes", "players", "sprint" and "jump". Reference lists from relevant articles were also scrutinized to find other potentially eligible studies.

6.2.2. Inclusion and exclusion criteria

Crossover, randomized, non-randomized and counterbalanced studies published in English were considered for inclusion and no age or sex restrictions were imposed. Studies were included if the following criteria was met: (I) at least one of the study's group was submitted to a CT intervention containing lower-body exercises, in which CT consisted of biomechanically similar (i.e., same movement pattern) heavy load resistance training exercises combined with plyometric/explosive exercises, set for set, in the same workout (76, 80). Studies that combined strength training and plyometric in a different manner (e.g. all strength exercises in the first part of the workout and all plyometric in the end of the session) were not considered; (II) interventions were of at least 4 weeks; (III) participants were athletes currently engaged in team-sports activities, and presented no cardiovascular, metabolic, or musculoskeletal disorders and no history of doping or drug abuse; (IV) sprint or VJ were outcome variables measured.

With respect to the exclusion criteria, studies were not considered if: (I) the article was not published in English; (II) no full-text was available; (III) no CT intervention group was present; (IV) only acute effects were investigated; (V) participants were not team-sports athletes; (VI) sprint or VJ were not outcome variables.

6.2.3. Study selection

The initial search was conducted by one researcher (TTF). After the removal of duplicates, titles and abstracts were screened and studies not related to the review's topic were excluded. Following the first screening process, the full version of the remaining articles was read. Then, on a blind, independent fashion, two reviewers selected the studies for inclusion (TTF and AMR), according to the criteria previously established. If no agreement was obtained, a third party intervened and settled the dispute.

6.2.4. Data extraction and analysis

Mean, SD and sample size data were extracted by one author (TTF) from tables of all included papers. Whenever necessary, contact was made with the authors to get the data. Any disagreement was resolved by consensus (TTF, AMR), or third-party adjudication (PEA). The meta-analysis and statistical analysis were performed using Review Manager software (RevMan 5.2; Cochrane Collaboration, Oxford, UK) and Comprehensive Meta-analysis software (Version 2; Biostat, Englewood, NJ, USA). For each study, mean differences and 95% confidence intervals (CI) were calculated with Hedges' g (157) for continuous outcomes.

Each mean difference was weighted according to the inverse variance method (158). Since sprint time and VJ height were assessed by different methods, the mean differences were standardized by dividing the values with their corresponding SD. The standardized mean difference (SMD) in each trial was pooled with a random effects model (159). The ESs were calculated using Cohen's d with the following equation (160), for paired samples:

$$ES = \frac{M_{pre} - M_{post}}{SD_{pre}}\left(1 - \frac{3}{4n - 5}\right)$$

where M_{pre} is the mean value before the CT intervention, M_{post} is the mean after the intervention, n is the sample size of CT group and SD_{pre} is the SD pre-intervention. Additionally, for independent samples (training and control group (CG)), the ESs were calculated with the formula (160):

$$ES = \frac{M_1 - M_2}{SD_{pooled}}$$

where M_1 is the mean value of the intervention group post CT intervention, M_2 is the mean of the CG after the intervention and the SD_{pooled} is calculated:

$$SD_{pooled} = \sqrt{\frac{SD_1^{2} + SD_2^{2}}{SD_{pooled}}}$$

ESs were considered small (ES = 0.2), medium (ES = 0.50) and large (ES = 0.80) (160). The data analysis was focused on the magnitude of effects obtained.

Heterogeneity among studies was assessed using I^2 statistics. I values range between 0% and 100% and are considered low, modest or high for < 25%, 25 - 50%, and > 50%, respectively. Heterogeneity may be assumed when the p-value of the I test is < 0.05 and may be due to the variability between the characteristics of the participants of the studies included (age, sex, etc) (161).

Potential moderating factors were evaluated by subgroup analysis comparing trials grouped by dichotomous or continuous variables potentially influencing sprint time and VJ height. Median values of continuous variables were used as cut-off values for grouping trials. Changes in potential moderating factors were expressed and analysed as post- minus pre-intervention values. Publication bias was evaluated by estimating funnel plot asymmetry test. Statistical significance was considered for $p \leq 0.05$.

6.2.5. Risk of bias

Methodological quality and risk of bias were assessed by visual interpretation of the funnel plot, by two authors independently (TF, AM), with disagreements being resolved by third part evaluation (PA), in accordance with the Cochrane Collaboration Guidelines (158).

6.3. RESULTS

6.3.1. Characteristics of included studies

A total of 1593 records were identified through database searches and 3 studies through reference lists. After abstract screening, from the 328 studies that were left following duplicates removal, 296 studies were excluded. As a result, 32 studies were assessed for eligibility. Of these, 23 were excluded for not meeting the inclusion criteria. Consequently, 9 studies (73-75, 88, 94-96, 153, 154) were included in this meta-analysis (Figure 1).

From the studies included, 4 (73, 74, 95, 153) presented two CT groups which accounted for a total of 9 subgroups analysed for the sprint variable and 8 for VJ. A CG was present in 5 of the studies (73, 94-96, 154).

The quality of the trials, according to a PEDro scale (162) was high. The mean score was 6.44 ± 1.01 out of a possible 10 points (Table 1).

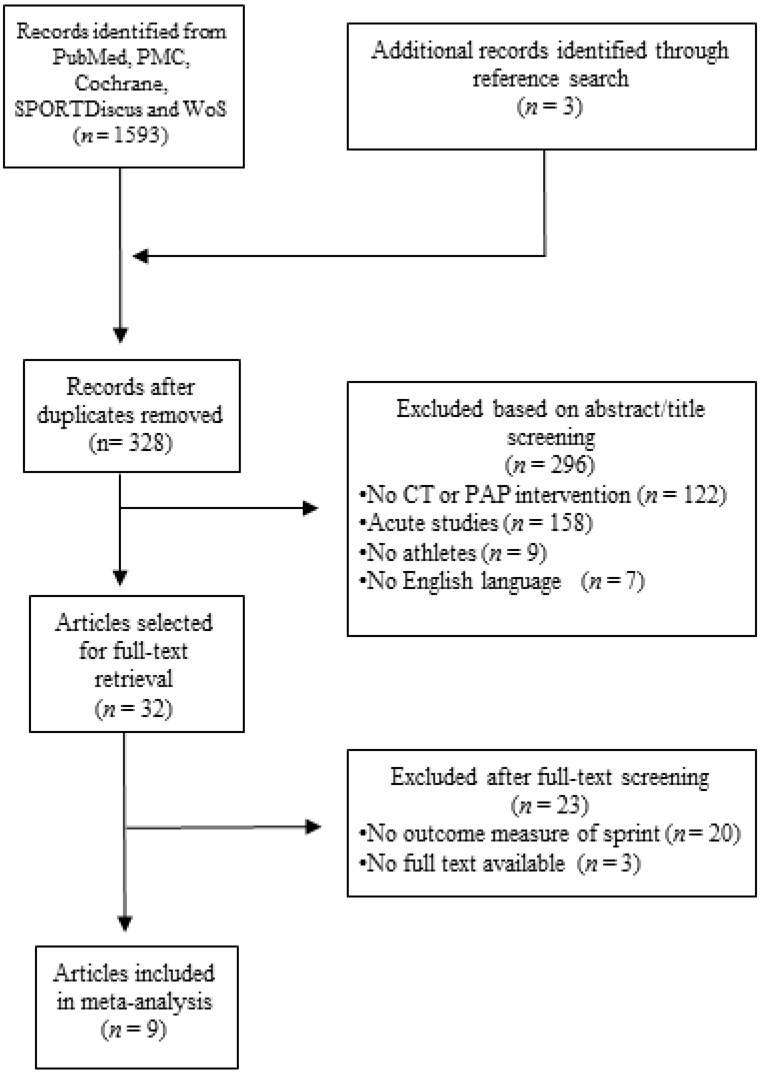

Figure 1. Flow diagram of the process of study selection

Table 1. PEDro Scale scores of the studies included in the meta-analysis.

PEDro Scale Items	Alves et al., 2010	Brito et al., 2014	Cavaco et al., 2014	Dodd et al., 2007	Faude et al., 2013	Kukric et al., 2012	McMaster et al., 2014	Mihalik et al., 2008	Watts et al., 2014
1. Eligibility criteria (item does not score)	1	1	1	1	1	1	1	1	1
2. Random allocation	1	1	1	1	1	1	1	-	1
3. Concealed allocation	1	1	1	1	1	1	1	-	1
4. Similar groups at baseline	1	1	1	1	1	-	1	-	1
5. Blinding of subjects	-	-	-	-	-	-	-	-	-
6. Blinding of therapists	-	-	-	-	-	-	-	-	-
7. Blinding of assessors	-	-	-	-	-	-	-	-	-
8. Measure of one key outcome – 85% of subjects	1	1	1	1	-	1	1	1	1
9. Intention to treat	1	1	1	1	1	1	1	1	1
10. Between-group comparison	1	1	1	1	1	1	1	1	1
11. Point estimates and variability	1	1	1	1	1	1	1	1	1
Total Score	7	7	7	7	6	6	7	4	7

6.3.2. Characteristics of the interventions

The different CT intervention groups' characteristics are present in Table 2. The intensity of the lower-body heavy resistance exercises performed ranged from 50% to 100% 1RM and the plyometric/power exercises from body mass to 75% 1RM (loaded CMJ). The interventions ranged from 4 to 10 weeks of duration with a frequency of 1 to 4 sessions/week. The distances covered in sprint assessment ranged from 15 to 30 m. Regarding VJ, 3 studies used a force platform to record jump performance (96, 153, 154), 2 utilized a Vertec device (75, 88) and 1 used a jump mat (95).

Table 2. Characteristics of the studies included in the meta-analysis and complex training interventions, sprint time and vertical jump assessment.

Study, year	n			Age	Sport	Level	Complex Training intervention					Sprint			Vertical Jump		
	CG	CT	♀ (%)				Type	Freq (wk⁻¹)	ICRI	Duration (wks)	Intensity CA	Measure	Units	Distance (m)	Measure	Unit	Type
Alves et al. (95), 2010	6	9	0	17.4 ± 0.6	Soccer	D1	**CT1:** CTP1- Squat + High Skipping CTP2- Calf Raises +VJ CTP3- Leg ext + VJ from seated position	1	No data	6	85% 1RM	Photoelectric cells	sec	15	Jump mat	cm	CMJ
		8	0				**CT2:** Same as CT1	2									
Brito et al. (94), 2014	21	12	0	19.9 ± 0.5	Soccer	U-D1	**CT:** CTP1- Squat + High Skipping CTP2- Calf Raises +VJ CTP3- Leg ext + VJ from seated position	2	20 sec	9	85% 1RM	Photoelectric cells	sec	20	N/A	N/A	N/A
Cavaco et al. (73), 2014	6	5	0	13.8 ± 0.45	Soccer	U-D1	**CT1:** CTP1- Squat + Sprint CTP2 – Squat + Sprint with ball	1	No data	6	85% 1RM	Photoelectric cells	sec	15	N/A	N/A	N/A
							CT2: Same as CT1	2									

Dodd et al. (88), 2007	—	32	0	20.5 ± 2.5	Baseball	U-D1	**CT**: 3 HR combined with 3 PLY	2	<10 sec	4	85% 1RM	Hand-held stop watch	sec	18.3	Vertec device	inch	Aba
Faude et al. (96), 2013	8	8	0	23.1 ± 2.7	Soccer	U-D1	**CT**: 2 dav routine D1: Unilateral Half-Squat + Single Leg Jumps D2: 2 of 4 CTP + 1 soccer- specific CTP1- Half-Squat + DJ CTP2- Calf Raises + High Straight Jumps CTP3- Lateral Half-Squat + Lateral CTP4- Step-ups + Bounding Jumps	2	<10 sec	7	90%/ 50-60% 1 RM	Photoelectr ic cells	sec	30	Force platform	cm	CMJ
Kukric et al (154). 2012	10	10	0	16.5 ± 0.5	Basketball	U-D1	**CT**: CTP1- Standing on toes + Single leg jumps CTP2- Leg Press + Jump over Hurdles CTP3- Step forward + Telemark jumps CTP4- Half-Squat + Jump over Hurdles	2	5 min	10	80% RM	N/A	N/A	N/A	Force platform	cm	Aba

McMaster et al. (74), 2014	—	14	0	20.9 ± 1.6	Rugby	D1	**SHB**: 4 day routine D1: CMJ + CM bench throws Power Cleans + Jammer Press DB Snatch D2: CTP1- Bench Press + Bench Press CTP2- Chin-ups + High Pulls CTP3- DB Floor Press + DB rows D3: CTP1- Back Squat + Squat Jumps CTP2- Bulgarian Split Squat + Speed D4: CTP1- Incline DB press+ Alternate DB bench press CTP2- Hip Thrusts + Calf Raises **SLB**: Same as SHB	4	2 min	5	85-100/60-75% RM	Photoelectric cells	sec	20	N/A	N/A	N/A
Mihalik et al. (75), 2008	—	15	67	20.3 ± 2.2	Volleyball	D1	**CT**: Squat + Depth Jump Single Leg Lunge + Split Squat Jump Deadlift + Double Leg Bounds	4	2 min	4	60% 1RM	N/A	N/A	N/A	Vertec device	cm	Aba

Watts et al. (153), 2014	—	4	0	16.8 ± 0.6	Volleyball	D1	**HRS**: 2 day routine D1: CTP1- Power Snatch + Medicine CTP2- Back Squat + Depth Jumps Front Squat D2: CTP1- Power Clean + Spike Jump CTP2- Front Squat + Standing Long Jumps	4	2 min	4	90% 3RM/ 90% 1RM	N/A	N/A	N/A	Force platform	cm	CMJ
		5	0	17.9 ± 1.1			**LRS**: Same as HRS										

Data are mean, mean ± SD, n or range. C = control group; CT = complex training exercise-group; ICRI = Intracomplex Rest Interval; CA = Conditioning Activity; RM = Repetition
Maximum; D1 = Division 1; U-D1 = Under Division 1; CTP = Complex Pair; HR = Heavy Resistance Exercises; PLY = Plyometric Exercises; CT1 = Complex Training group I;
CT2 = Complex Training group 2; SHB = Strength Heavy Ballistic complex training group; SLB = Strength Light Ballistic complex training group; HRS = High Reactive Strength group;
LRS = Low Reactive Strength group

6.3.3. Main effects analysis

When all studies and respective CT groups were examined, results indicated medium training effects (ES = 0.73) on sprint performance ($p \leq 0.05$) and small (ES = 0.34) on VJ height ($p = 0.07$) following CT interventions (Figures 2 and 3). Furthermore, in the studies that presented a CG, experimental groups presented better post-intervention sprint time (ES = 1.01; $p = 0.05$) and VJ height (ES = 0.63; $p = 0.02$) than CG (Figures 4 and 5).

Study or Subgroup	Post intervention Mean	SD	Total	Pre intervention Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Alves et al., 2010 (CT1)	2.38	0.09	9	2.56	0.1	9	9.4%	-1.80 [-2.94, -0.66]
Alves et al., 2010 (CT2)	2.49	0.07	8	2.57	0.1	8	10.3%	-0.88 [-1.92, 0.16]
Brito et al., 2014	3.05	0.07	12	3.25	0.09	12	9.8%	-2.40 [-3.49, -1.30]
Cavaco et al., 2014 (CT1)	2.59	0.18	5	2.72	0.25	5	8.3%	-0.54 [-1.82, 0.74]
Cavaco et al., 2014 (CT2)	2.46	0.15	5	2.6	0.14	5	7.9%	-0.87 [-2.20, 0.46]
Dodd et al., 2007	2.88	0.09	32	2.9	0.09	32	16.5%	-0.22 [-0.71, 0.27]
Faude et al., 2013	4.27	0.09	8	4.26	0.15	8	10.9%	0.08 [-0.90, 1.06]
McMaster et al,2014 (CTH)	2.99	0.07	14	3.02	0.08	14	13.4%	-0.39 [-1.14, 0.36]
McMaster et al,2014 (CTL)	3	0.09	14	3.03	0.08	14	13.4%	-0.34 [-1.09, 0.41]
Total (95% CI)			**107**			**107**	**100.0%**	**-0.74 [-1.22, -0.25]**

Heterogeneity: $Tau^2 = 0.30$; $Chi^2 = 19.99$, $df = 8$ ($P = 0.01$); $I^2 = 60\%$

Test for overall effect: $Z = 2.99$ ($P = 0.003$)

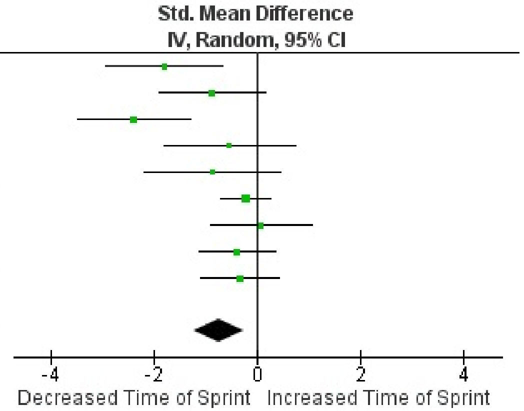

Figure 2. Standardized mean difference (SMD) between post and pre-intervention sprint time in CT-trained subjects. Squares represent the SMD[a] for each trial. Diamonds represent the pooled SMD across trials.

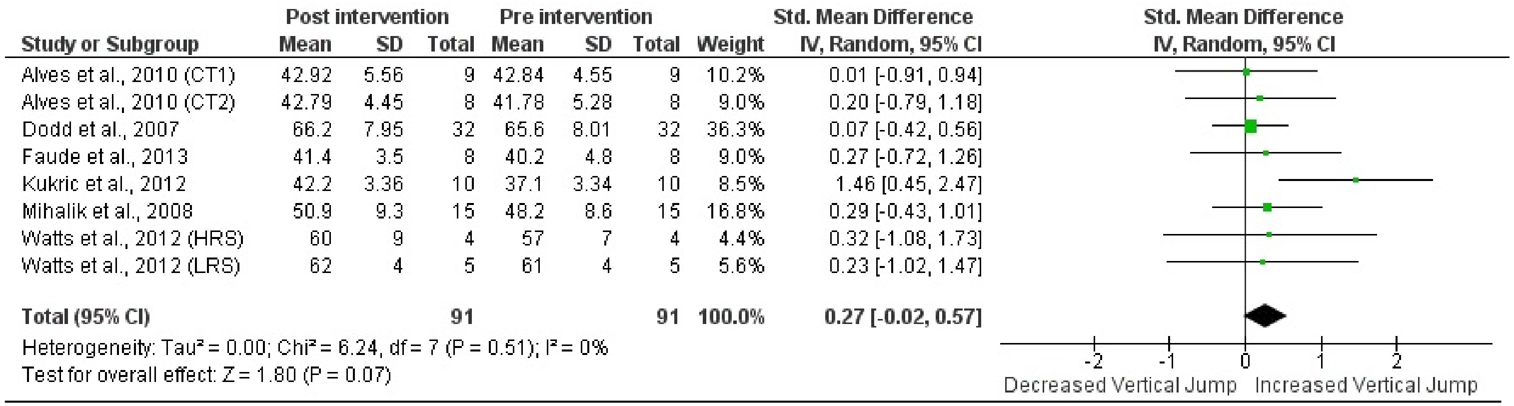

Figure. 3. Standardized mean difference (SMD) between post and pre-intervention VJ height in CT-trained subjects. Squares represent the SMD[a] for each trial. Diamonds represent the pooled SMD across trials.

Study or Subgroup	Complex Training Mean	Complex Training SD	Complex Training Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Alves et al., 2010 (CT1)	2.38	0.09	9	2.56	0.02	6	14.2%	-2.36 [-3.79, -0.94]
Alves et al., 2010 (CT2)	2.49	0.07	8	2.56	0.02	6	16.4%	-1.19 [-2.37, -0.01]
Brito et al., 2014	3.05	0.07	12	3.17	0.12	21	20.4%	-1.11 [-1.88, -0.35]
Cavaco et al., 2014 (CT1)	2.59	0.18	5	2.66	0.18	6	16.2%	-0.36 [-1.56, 0.85]
Cavaco et al., 2014 (CT2)	2.46	0.15	5	2.66	0.18	6	15.1%	-1.09 [-2.41, 0.22]
Faude et al., 2013	4.27	0.09	8	4.19	0.09	8	17.8%	0.84 [-0.20, 1.88]
Total (95% CI)			**47**			**53**	**100.0%**	**-0.83 [-1.65, -0.01]**

Heterogeneity: $Tau^2 = 0.70$; $Chi^2 = 16.03$, df = 5 (P = 0.007); $I^2 = 69\%$
Test for overall effect: Z = 1.99 (P = 0.05)

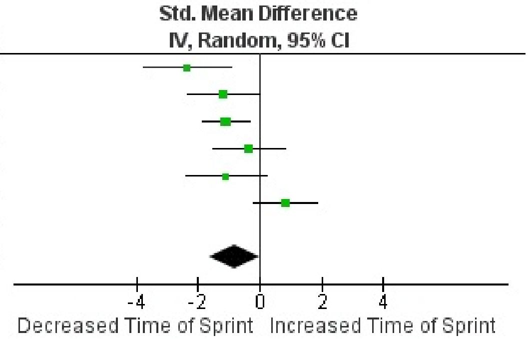

Figure. 4. Standardized mean difference (SMD) in post-intervention sprint time between CT-trained and control subjects. Squares represent the SMD[a] for each trial. Diamonds represent the pooled SMD across trials.

Study or Subgroup	Complex Training Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Alves et al., 2010 (CT1)	42.92	5.56	9	41.53	2.71	6	24.1%	0.28 [-0.76, 1.32]
Alves et al., 2010 (CT2)	42.79	4.45	8	41.53	2.71	6	22.9%	0.31 [-0.76, 1.38]
Faude et al., 2013	41.4	3.5	8	39.8	2.4	8	26.0%	0.50 [-0.50, 1.50]
Kukric et al., 2012	42.2	3.36	10	37.4	3.79	10	27.0%	1.28 [0.30, 2.27]
Total (95% CI)			**35**			**30**	**100.0%**	**0.62 [0.11, 1.13]**

Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 2.54$, df = 3 (P = 0.47); $I^2 = 0\%$
Test for overall effect: Z = 2.36 (P = 0.02)

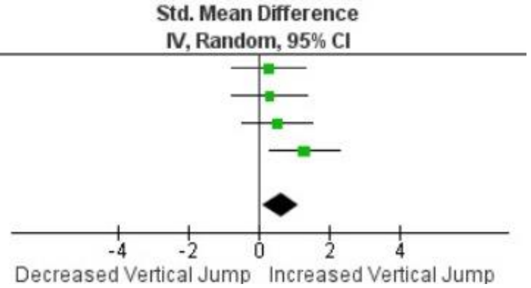

Figure 5. Standardized mean difference (SMD) in post-intervention VJ between CT-trained and control subjects. Squares represent the SMD[a] for each trial. Diamonds represent the pooled SMD across trials.

6.3.4. Subgroup analysis

Subgroup analysis assessing potential moderating factors for sprint time and VJ height are presented in Table 3. Regarding age, large ES were obtained for younger players (< 20 years) in sprint (ES = 1.13) and small in VJ (ES = 0.42), independent of the level of practice. For players over 20 years old, small ESs were found (sprint = 0.23; VJ = 0.20). With respect to the level of practice, an athlete was considered Division I (D1) if he was competing in first division of his respective sport, independent of the age category. All the players not competing in first division were considered under-Division I (U-D1). On sprint, both D1 (ES = 0.76) and U-D1 (ES = 0.70) athletes obtained medium training effects, independent of age On VJ, D1 athletes exhibited small ESs (ES = 0.2) and U-D1 medium (ES = 0.56).

Concerning training frequency, from all the studies that had VJ as an outcome variable, only one (95) had a frequency other than 2 times/week. Hence, subgroup analysis was only performed for sprint. Lower training frequencies induced a large training effect on sprint performance (ES = 0.84) whereas training 3 or more times/week exhibited small ESs (ES = 0.35).

Regarding the CA intensity, large ES (ES = 0.96) on sprint time was attained for intensities below 85% 1RM and small (ES = 0.25) for higher intensities (≥ 85%). As for VJ, results indicated a medium ES (ES = 0.64) with loads lighter than 85% 1RM. When the workout comprised loads heavier than 85% 1RM, trivial ES were found (ES = 0.15).

Regarding the duration of intervention, longer CT programs (≥ 6 weeks) presented large ESs for sprint (ES = 0.95) and small for VJ (ES = 0.45) while shorter training periods (< 6 weeks) showed small ESs (sprint = 0.29 and VJ = 0.22).

Regarding the number of sessions, performing less than 12 resulted in a medium training effect (ES = 0.74) for sprint and a trivial for VJ (ES = 0.18). Completing more than 12 sessions displayed a medium effect (ES = 0.71) for sprint and a large for VJ (ES = 0.81).

With reference to ICRI, for sprint, 2 studies (73, 95) did not specify the rest between the CA and the subsequent exercise and from the remaining investigations (74, 88, 94, 96), just one presented a different rest interval (74). Hence, no subgroup analysis was conducted for this variable. Regarding VJ, intervals longer than 2 min produced larger ESs (ES = 0.55) than shorter rest periods (ES = 0.15). However, 2 studies (73, 95) that did not report the time between the CA and the subsequent exercise were not considered in this subgroup analysis.

Finally, in relation to sport modality, athletes from team-sports in which jumping actions are more frequent and crucial for performance (basketball/volleyball) achieved medium training effects (ES = 0.55) after a CT intervention and players from other team-sports, trivial (ES = 0.12).

Table 3. Subgroup analyses assessing potential moderating factors for sprint time and vertical jump height in studies included in the meta-analysis

Group	Studies		Complex Training				
	Number[a]	References	SMD (95% CI)	*ES*	I^2	*P*	P_{Diff}
		Sprint					
Population characteristics							
Age							
≥20 years	4	(96, 74, 88)	-0.24 (-0.58, 0.09)	0.23	0	0.16	<0.05
<20 years	5	(95, 94, 73)	-1.33 (-2.02, -0.64)	1.13	43	<0.05	
Level							
Division 1	4	(74, 95)	-0.74 (-1.33, -0.15)	0.76	43	<0.05	<0.05
Under Division 1	5	(96, 88, 94, 73)	-0.74 (-1.57, 0.08)	0.70	72	0.08	
Exercise characteristics							
Frequency							
≥3 week^{-1}	2	(74)	-0.36 (-0.89, 0.16)	0.35	0	0.18	0.22
<3 week^{-1}	7	(96, 95, 88, 73)	-0.90 (-1.56, -0.23)	0.84	69	<0.05	
Intensity							
≥85% RM	3	(96, 74)	-1.07 (-1.82, -0.33)	0.25	70	<0.05	0.07
<85% RM	6	(95, 88, 73)	-0.27 (-0.73, -0.20)	0.96	0	0.26	
Duration							
≥6 weeks	6	(96, 95, 94, 73)	-1.06 (-1.82, -0.31)	0.95	63	<0.05	0.07
<6 weeks	3	(74, 88)	-0.29 (-0.65, 0.07)	0.29	0	0.12	
Total nº Sessions							
>12 sessions	4	(96, 74, 94)	-0.71 (-1.63, 0.20)	0.71	77	0.12	0.95
≤12 sessions	5	(95, 88, 73)	-0.75 (-1.33, -0.17)	0.74	43	<0.05	

Group	Studies			Complex Training			
	Number[a]	References	SMD (95% CI)	*ES*	I^2	***P***	P_{Diff}
			Vertical Jump				
Population Characteristics							
Age							
≥20 years	3	(96, 88, 75)	0.16 (-0.21, 0.54)	0.20	0	0.40	0.39
<20 years	5	(95, 153, 154)	0.45 (-0.09, 1.00)	0.42	21	0.10	
Level							
Division 1	5	(95, 153, 75)	0.21 (-0.23, 0.64)	0.2	0	0.35	0.50
Under Division 1	3	(96, 88, 154)	0.52 (-0.28, 1.33)	0.56	66	0.20	
Exercise characteristics							
Intensity							
≥85% RM	5	(95, 88, 153)	0.11 (-0.25, 0.48)	0.15	0	0.55	0.58
<85% RM	3	(96, 75, 154)	0.63 (-0.10, 1.35)	0.64	49	0.09	
Duration							
≥6 weeks	4	(96, 95, 154)	0.47 (-0.16, 1.10)	0.45	41	0.15	0.42
<6 weeks	4	(88, 153, 75)	0.16 (-0.21, 0.54)	0.22	0	0.39	
Total n sessions							
>12 sessions	2	(96, 154)	0.86 (-0.31, 2.02)	0.81	63	0.15	0.25
≤12 sessions	6	(95, 88, 153, 75)	0.15 (-0.18, 0.47)	0.18	0	0.37	
Intracomplex Rest							
≥2 minutes	4	(75, 153, 154)	0.58 (-0.01, 1.18)	0.55	24	<0.05	0.21
<2 minutes	2	(96, 88)	0.11 (-0.33, 0.55)	0.15	0	0.61	
Sport modality							
Jump predominance (Basketball/Volleyball)	4	(75, 153, 154)	0.58 (-0.01, 1.18)	0.55	24	0.05	0.18
Other Team -Sports	4	(96, 95, 88)	0.11 (-0.26, 0.48)	0.12	0	0.56	

Data are mean, mean ± SD, n or range. C = control group; CT = complex training exercise-group; ICRI = Intracomplex Rest Interval; CA = Conditioning Activity; RM = Repetition
Maximum; D1 = Division 1; U-D1 = Under Division 1; CTP = Complex Pair; HR = Heavy Resistance Exercises; PLY = Plyometric Exercises; CT1 = Complex Training group I;
CT2 = Complex Training group 2; SHB = Strength Heavy Ballistic complex training group; SLB = Strength Light Ballistic complex training group; HRS = High Reactive Strength group;
LRS = Low Reactive Strength group

6.3.5. Evaluation of potential bias

At evaluation of potential bias, visual interpretation of the funnel plot for the SMD between pre and post intervention sprint time and VJ height in CT participants was considered notably symmetrical, suggesting the absence of a significant publication bias. Similar results were obtained for the evaluation of potential bias of the SMD in post-intervention sprint time and VJ height between CT and CG athletes.

6.4. DISCUSSION

To the best of our knowledge, this is the first meta-analysis focusing on the short-term adaptations on sprint and VJ performance following CT in team-sports. The main findings indicated that this type of training lead to positive medium effects on sprint performance, over distances between 15 and 30 m. Regarding VJ height, small but positive effects were also found. Our results support the idea that CT, consisting on heavy resistance exercises coupled with plyometric/explosive exercises, set for set, on the same session, contributes to enhanced sprint and VJ performance (76, 80, 100). The training variables that seem to most influence this positive response to CT in team-sports are the duration of intervention (≥ 6 weeks), the CA intensity (< 85% 1RM) and the ICRI (≥ 2 min).

A second finding within the present meta-analysis is that, in the studies where a CG was present (73, 94-96, 154), intervention groups performed better than CG in both sprint and VJ. This is an interesting discovery given that players in CT and CG performed the same team practices, most probably containing short accelerations, sprinting, jumping and other high-intensity actions characteristic of team-sports (1, 163, 164). Therefore, we may assume that the increments found in sprint ability and VJ were due to the CT stimulus and not to the team practice (17).

An examination of the included studies shows discrepancies regarding sprint and VJ adaptations to CT. Therefore, due to such inconsistencies found in literature, the subgroup analysis performed focused on identifying potential moderating factors explaining the dissimilar adaptations following CT.

6.4.1. Age and level

The present meta-analysis showed that the ESs for sprint and VJ adaptations following CT interventions were greater in younger players (< 20 years), independent of the level of practice. It is possible that younger players had no sufficient strength training background, and for that reason any training stimulus would promote positive adaptations in performance, with or without PAP or combination of loads (151). In fact, in the study by Brito et al. (94), in which CT was compared to resistance training alone and plyometric only programs, no differences were found between protocols.

Concerning level of practice, D1 players showed slightly higher ES (ES = 0.76) than U-D1 (ES = 0.70) for sprint. Previous data (165) showed that increments in sprint are associated with the level of practice. However, the positive medium effects obtained by both subgroups suggest that CT may be a suitable option to increase sprint performance independent of the athletes' level. As for VJ, U-D1 (ES = 0.42) and D1 players (ES = 0.20) presented small ESs, independent of age. It has been demonstrated that elite soccer players have higher percentages of fast muscle fibers compared to non-elite (166) and that strength levels (151, 167) and fiber type composition (168) may influence the magnitude of PAP, a possible mechanism contributing to performance gains with CT (76, 80, 100). Also, it has been demonstrated that higher level athletes are better responders to PAP or CT programs (151, 167). This contrasts with our findings regarding VJ, which may be possibly explained by the modest heterogeneity found in the U-D1 group, for this variable, indicating variability between the characteristics of the participants. However, reports of no differences being obtained, following CT acute protocols, among participants with dissimilar expertise, training background or strength levels have also been reported (91, 169).

6.4.2. Training frequency

No analysis of training frequency was conducted for VJ since all CT groups but one (CT1 (95)) performed 2 sessions/week. On sprint, results indicated that lower training frequencies (< 3 $week^{-1}$) exhibited greater effects (ES = 0.84), than training 3 or more days. According to Seitz et al. (165), high resistance training frequencies may generate a greater stress, overwork and eventually impair performance, when performed concurrently with regular team practice. However, Seitz et al. (165) analyzed several resistance training programs and not only CT protocols. When considering solely CT, previous research (73, 95) indicated that a frequency of 2 or less times/week is as effective in increasing sprint performance as 3 or more sessions/week. Moreover, when a certain body part is actively used during competition or sport-specific training, lower weekly frequencies are needed to maintain performance levels (170).

6.4.3. Duration of intervention and total number of sessions

Concerning the duration of intervention, longer interventions were found to produce greater effects on sprint and VJ performance (sprint = 0.95; VJ = 0.45). This higher magnitude of effect in sprint seems to be in line with previous findings that stated that longer resistance training interventions (> 8 weeks) resulted in improved speed development in soccer as well as rugby and American football players (137). In basketball players, no significant correlations were identified between program duration and increments in VJ following resistance training interventions (56). However, it is worth noting that, on their respective reviews, both Bolger et al (137) and Sperlich et al. (56) referred to various resistance-based methods and not only to CT programs. On a practical perspective, the large effect (ES = 0.95) observed on sprint performance for programs over 6 weeks seem to indicate that, adaptation wise, longer CT program should be recommended. Also, 6 weeks of duration may be a good reference for S&C professionals in terms of program duration.

With respect to the number of sessions, for sprint, 12 or less CT sessions displayed a medium training effect (ES = 0.74), as well as performing over 12 (ES = 0.71). As for VJ, the opposite was observed with a shorter number of sessions resulting in lower ESs (ES = 0.18) than interventions consisting on more than 12 workouts (ES = 0.81). However, it is important to state that only 2 CT groups performed less than 12 sessions and that a modest heterogeneity ($I^2 = 63$) was found in this particular subgroup. Nevertheless, according to the data here obtained, less training sessions are needed to achieve performance improvements in sprint compared to VJ. In fact, it has been suggested that speed gains are greater when resistance training is combined with locomotor training (137). All the participants included in the present meta-analysis were athletes currently competing in team-sports and so, apart from the CT protocols, players were engaged in sprinting actions during practice and or competition. Considering that sprinting activities are more frequent than jumping in basketball (142), rugby (140) and soccer (139, 164), it can be speculated that this is a possible rationale why, when CT is combined with regular team practice/competition, less sessions are necessary to elicit performance improvements in sprint when compared to VJ. However, further analysis of the influence of horizontally and vertically oriented exercises in CT may add valuable insight on how to maximize sprint or VJ post-intervention adaptations (171).

6.4.4. Intensity of the conditioning activity

With regards to the intensity of the CA, for both variables, intensities below 85% 1RM in the CA exhibited greater training effects (sprint = 0.96; VJ = 0.64) than maximal loads (> 85% 1RM; sprint = 0.25; VJ = 0.15). The type of load of the CA influences the PAP response (78, 79). Wilson et al. (79) reported that moderate intensities, ranging from 60% to 84% 1RM produced a significantly higher PAP response than loads heavier than 85% 1RM, independent of training experience or strength levels whereas Seitz and Haff (78) indicated that maximal loads elicited greater PAP responses. It seems that PAP may be mediated by the individual's strength level, since stronger athletes present higher PAP with maximal loads (78, 79, 84, 85, 167) while weaker subjects achieve it with sub-maximal loads (78). It has been suggested that this occurs because when weaker individuals exercise with maximal loads, fatigue may exceed potentiation (78). Theoretically, although PAP responses are highly individualized (77, 78, 100) and there is no clear agreement on its role as the main mechanism behind CT (82), a greater PAP could result in larger improvements on performance, following a CT protocol, if the explosive exercise was completed while the muscles were in a potentiated state (101). With the data here obtained, it can be argued that the analyzed players' strength levels were not high enough for them to be able to achieve greater increments on VJ performance when heavy loads were utilized, and that is why larger training effects were elicited with loads lighter that 85% 1RM.

6.4.5. Intracomplex rest interval

Concerning the ICRI, a subgroup analysis was not possible to conduct for sprint performance. Two studies (73, 95) did not specify the rest between the CA and the subsequent exercise and from the remaining investigations (74, 88, 94, 96), just one presented a different rest interval (74). For VJ, the ICRI ranged from < 10 sec to 5 min. The data obtained showed that greater training effects were obtained with larger resting periods (ES = 0.55). This is in line with several studies (78, 79, 91) that have shown that the PAP response, although highly individualized, is larger when longer intervals are allowed between the CA and the subsequent explosive action. Seitz and Haff (78) indicated that rest intervals between 5 to 8 min exhibit larger PAP effects than ones ranging from 0.3 to 4 min. Nevertheless, it is worth noting that the studies reviewed by Seitz and Haff (78) were acute studies and not training interventions. This is an important aspect to consider, because when it comes to CT protocols composed by several sets of several complex pairs it is not practical to utilize ICRIs of 8 min, as the training session would take too long to be completed. Following a CA both potentiation and fatigue co-exist and the balance between these two responses is crucial if performance enhances are to be achieved (77-79). Sale (81) identifies two dilemmas related to the PAP and fatigue responses after a CA. The first is that more intense CAs may lead to a higher potentiated state but also generate greater levels of fatigue. The second is that longer rest intervals may allow for a better recovery of fatigue but also result in a greater decrease of the PAP mechanism (81). When it comes to designing a CT protocol it is necessary to find an adequate balance and to take into account that longer ICRIs are recommended but that in an everyday setting, recovery periods of 5-8 min may not be practical.

6.4.6. Team-sports modality

The influence of sport modality was analyzed only for VJ because it was possible to differentiate among sports where jumping actions are crucial for high performance (such as basketball (1) and volleyball (172)) and other modalities (soccer, rugby or baseball). Jump predominant sports exhibited medium effects (ES = 0.55) whereas non-predominant, trivial (ES =0.12). This may be related to the specificity of training background which is known to influence performance (111), or to the fact that during training and competition, a higher number of VJ are performed by basketball (1) and volleyball (172) players in comparison to other sports (163) and that this specific stimulus lead to medium effects in the magnitude of improvement in VJ.

Regarding sprint, however, from the 9 CT intervention groups analyzed, 6 consisted on soccer players (73, 94, 95), 2 on rugby players (94) and one on baseball athletes (88). For this reason, a subgroup analysis was not performed, as there was no modality in which sprint could be considered more crucial to performance than others.

6.4.7. Limitations

Some limitations can be identified within the present meta-analysis. First, the scarce number of studies included, due to the few publications on CT interventions on team-sports that have sprint or VJ as an outcome variable. Second, not all analyzed CT programs were compared to a CG or to other training methods aimed at developing strength and/or power. Moreover, the heterogeneity in athlete characteristics (i.e., age, level, training history) is another factor that should be taken into account and that may be considered a limitation. Also, the training mechanisms outside the CT interventions were not considered in the analysis, as well as the resistance training protocols performed in the weeks prior to the CT programs. Finally, different methodological procedures and instruments were used to assess performance (VJ, particularly) in the different studies. Hence, it cannot be ruled out that some outcome values may have been affected by the method used.

6.5. CONCLUSIONS AND PRACTICAL APPLICATIONS

CT is a training method aimed at developing both strength and power, which has a direct effect on sprint and VJ performance. When outlining the season planning for team-sports, S&C professionals should take into consideration that this may be a suitable method as it produces medium training effects on sprint performance and small positive effects on VJ.

Although the response to CT is highly individualized, based on the present results, programs lasting over 6 weeks, with a frequency of 2 sessions/week and CA activities with loads lighter than 85% 1RM seem to be the most adequate to improve sprint performance. Regarding VJ, CT protocols with a duration of more than 6 weeks, with 12 or more total sessions, CA activities below 85% 1RM and ICRI longer than 2 min appear to be the most effective on team-sports athletes. Finally, players from sports in which jumping actions are more frequent and crucial for high performance (basketball/volleyball) seem to benefit the most from CT.

VII – STUDY 3

VII. STUDY 3:

SHORT-TERM OPTIMAL LOAD TRAINING VS A MODIFIED COMPLEX TRAINING IN SEMI-PROFESSIONAL BASKETBALL PLAYERS

7.1. INTRODUCTION

Basketball is a sport that incorporates aerobic and anaerobic metabolic processes and it is characterized by intermittent high-intensity explosive actions such as: jumping, sprinting or changing direction (2). According to the literature, maximal power is crucial in most sport-specific movements (49), particularly in basketball (173), in which VJ and COD, actions that require substantial power production, are determinants of high performance (9, 10). Furthermore, maximal power, along with strength, has been shown to differentiate competition levels among basketball players (10). Therefore, applied research on training programs designed to improve strength and power without the use of heavy loads is of great interest for sport scientists and practitioners.

During the season, different resistance training methods are prescribed to improve athletic performance in team-sports (16, 43, 44, 174). Amongst the several methodologies, OLT and CT are two training protocols that are becoming increasingly popular within the S&C and scientific communities, as supported by recently published meta-analyses (102, 174).

In OLT, athletes perform a given exercise with the load that maximizes its mechanical power (49, 102). This load is usually determined as a percentage of the 1RM or percentage of body mass (102, 109) and has been reported to provide the best stimulus for power enhancement (44, 49, 102, 175). Moreover, this method has been suggested to result in the greatest increments in dynamic athletic performance (176).

The load that maximizes power output is exercise-specific and the same relative intensity cannot be applied to all exercises (102, 111). Firstly, each exercise has unique biomechanical and neurophysiological characteristics that influence power output (102). Secondly, an athlete's training background influences muscle mechanics, cross-sectional area or fiber type distribution, which is known to affect power production (111). In a recent study, Loturco et al. (44) reported that 6 weeks of OLT resulted in improved 10 m and 20 m sprint times and power production when compared to a classic strength-power periodization in soccer players. These promising results seem to indicate that OLT may be a suitable option to apply in team-sports, although further research is necessary.

CT is a method that combines, set by set in the same session, biomechanically similar (i.e., comparable kinematics) high-intensity resistance exercises with plyometric or power exercises, performed at maximal movement velocities (76, 80). A half-squat followed by a CMJ is an example of a complex pair, the term used to describe two consecutive exercises combined (76, 80). The mechanisms underlying the adaptations following CT are still unclear. On the one hand, it has been suggested that high-intensity resistance exercises increase motoneuron excitability and reflex potentiation, creating enhanced training conditions for subsequent neuromuscular power adaptations (76). On the other, PAP, a phenomenon characterized by an acute muscle force or power output enhancement after a maximal or near-maximal contraction (77), is believed to be responsible for performance improvements following CT (151, 174). Greater PAP responses have been reported to occur in stronger athletes, when high-intensity resistance exercises are performed (≥ 85% of 1RM) and after longer recovery intervals (> 5 min) between the CA and the subsequent athletic task (78). However, the latest evidence regarding team-sports suggest that heavy loads may not be the most appropriate to elicit PAP (177), or to be used in CT interventions (174). This type of loading can negatively affect the fatigue-PAP relationship, leading to higher levels of transient fatigue and lesser potentiation (77).

A recent meta-analysis investigated the short-term adaptations following CT in team-sports (174) and reported positive training effects on sprint and VJ performance. However, it remains unclear if CT is more effective than other training programs designed to improve strength and power in trained athletes (101, 174). Moreover, it is still unknown how modifying the characteristics of CT programs may affect performance. Current literature suggests that, individually, both OLT and CT are methods likely leading to performance improvements in team-sports. However, to the best of our knowledge, no previous investigations have addressed their combined effects within a CT protocol during a basketball competitive season. Given the potential benefits reported when employing optimal loads in team-sports (44), we considered relevant to investigate how a CT consisting on a moderate intensity CA followed by an exercise performed with a load that maximizes power output might influence neuromuscular adaptations.

Therefore, the aims of this research were: (I) to investigate the effects of an OLT and a novel modified CT (MCT: complex pairs consisting on the same exercise performed with a moderate (80% of 1RM) and an individually determined optimal load) on neuromuscular performance in basketball players; (II) to compare their effects after a 6-week intervention.

7.2. METHODS

7.2.1. Study design

A quasi-experimental, short-term (6-week intervention and 2-week testing) study was conducted. Intra- and inter-participants differences were analysed in a pre- and post-test design. Players were matched by playing position (guards, forwards and centres) and, then, randomly assigned (Research Randomizer Software 4.0; Lancaster, Pennsylvania) to one of two training protocols: OLT or a MCT. During the intervention period (competitive phase of the 2016/2017 season), participants played 7 official games and participated on 24 basketball practices. With the coaches' agreement, the microcyle planning was similar during the 8-week period. Basketball training was prescribed by the coaching staff and consisted mainly on small-sided basketball games, 5 x 5 scrimmage, shooting and fast-break drills. Internal load was monitored with the session RPE (178) and kept constant during the research period, with *very likely* trivial differences identified between training groups (an average total weekly training load of 2316 ± 191 and 2303 ± 211 AU for OLT and MCT, respectively).

7.2.2. Participants

Initially, 23 semi-professional male basketball players competing in Spanish League EBA (4th Division), with at least 8 years of playing experience and 1-year participation in resistance training, volunteered to participate. No player sustained any severe injury in the 2 years prior to the study and no disease or medication intake was reported during the intervention. Players were fully informed about the procedures and signed a written consent approved by the local Ethics Committee in accordance with the 2013 Helsinki Declaration. All participants underwent a physical examination by the team physician and were cleared of any endocrine disorders that might limit their ability. They were instructed to maintain their normal diet habits and their team´s regular practice schedule (4 training sessions per week). During the intervention, 2 players were promoted to the club's professional team and 3 sustained injuries unrelated to the training protocols. Therefore, a total of 18 players (age: 21.3 ± 4.3 years, height: 194.5 ± 11.4 cm, body mass: 90.9 ± 14.8 kg) were included in the statistical analysis, as they completed at least 85% of the total number of sessions.

7.2.3. Testing procedures

Testing was completed in a research centre and at each team's pavilion (temperature: 21 - 23º C, humidity: 57 - 61%). Procedures were carried out in two separate days, after 36h of rest. On day 1, players reported to the research centre at 10:00 and completed the following sequence: (I) anthropometric measurements; (II) warm-up; (III) maximum dynamic strength and power-load profiling in half-squat, bench press and hip thrust. The exercise order was randomized for each player, with the condition that the bench press was always the second exercise, to avoid performing two lower-body exercises consecutively. Warm-up consisted on 8 min treadmill running, followed by dynamic stretching, core and lower-body activation drills. On day 2, in the pavilion, procedures were: (IV) warm-up; (V) CMJ and SLJ; (VI) 10 m sprint and (VII) T-test. The testing sequence was randomized for each player. Warm-up involved the same exercises as in day 1, with the addition of accelerated running drills with and without COD. After the 6-week protocols, procedures were repeated following the exact same methods. For all tests performed, within-session test-retest reliability was assessed by the coefficient of variation (CV).

7.2.3.1. Anthropometric measurements

The same researcher (ISAK Level-1 certified) performed the anthropometric measurements, in both pre- and post-test. Height, body mass, circumferences and skinfold thickness were determined for each player. The relaxed and flexed arm, waist, hip and leg circumferences were measured twice with a 2 m measuring tape (CESCORF, Porto Alegre, Brazil) and the average of the two values was taken. The skinfold thickness was assessed in accordance with ISAK guidelines (179) using a set of Harpenden Skinfold Calipers (Baty International, West Sussex, UK). Eight skinfolds were measured: biceps, triceps, subscapular, iliac crest, supraspinal, abdominal, anterior thigh, and medial calf. All skinfolds were determined three times and the average of the measurements was considered as the true skinfold thickness (intra-rater CV = 0.75%). Percentage of body fat was estimated with the Faulkner Equation (180) and percentage of muscle mass with the modified Matiegka equation (181). The sum of the eight skinfolds was also determined.

7.2.3.2. Maximal dynamic strength

Maximal dynamic strength was assessed for both lower- and upper-limbs by estimating the half-squat, bench press and hip thrust 1RM. All exercises were performed on a modified Smith machine with a linear encoder (Chronojump-BoscoSystem, Spain) attached to the barbell, interfaced with a computer. All data were recorded with the Chronojump-BoscoSystem Software. Before the testing, participants executed two warm-up sets with a submaximal load that allowed them to complete 8-10 repetitions. Then, to estimate the half-squat 1RM, players executed 3 repetitions with their perceived 4 - 6RM (based on their previous experience and training loads). They were asked to descend to a position of 90º of knee flexion and were verbally encouraged to move the barbell as fast as possible in the concentric phase. The mean propulsive velocity (MPV) of each repetition was recorded, and the highest value was used to estimate the 1RM. Since a very strong linear relationship has been reported between the MPV and the percentages of the half-squat 1RM, the estimated 1RM (CV = 2.7%) was calculated (182):

$$\%\ \textit{Half-squat 1RM} = -105.05 \times MPV + 131.75$$

For the bench press, similar procedures were followed. The barbell was lowered to the point where it nearly touched the chest and the concentric phase was performed at maximal velocity. The 1RM was estimated (CV = 2.2%) based on the theoretical load at zero velocity and the average velocity (AV) of the bar (183):

$$\%\ \textit{Bench Press 1RM} = \frac{AV - 1.7035}{-0.0146}$$

For the hip thrust, the 1RM was determined following traditional guidelines (184), as no equation that allowed an accurate prediction of the maximum dynamic strength in this exercise was found on literature. Spotters were present to assist in racking the resistance and to ensure that participants maintained a consistent and safe technique, in line with the guidelines presented by Contreras et al. (185).

7.2.3.3. Power-load profiling

Power-load profiles were calculated for the half-squat, bench press and hip thrusts using the relative intensity corresponding to 30%, 45%, 60% and 75% of the previously estimated 1RM, to determine the intensity that maximized power output using the same lineal encoder. Players completed 3 repetitions with each load, performing a 3 s eccentric phase followed by a maximal velocity concentric phase. Peak power was recorded for each repetition and the load corresponding to its highest value was considered for the training protocols. A 3 min rest was allowed between trials.

7.2.3.4. Horizontal jump test - Standing long jump

SLJ was performed as described elsewhere (122). Participants performed two practice trials and then two test trials separated by 1 min rest. The horizontal distance was measured to the nearest 0.01 m (CV = 2.5%). Only the best result was considered for analysis. This test has been recommended for basketball players' assessment (186).

7.2.3.5. Vertical jump test - Countermovement jump

CMJ was performed on a Kistler 9286BA portable force platform (Kistler Group, Winterthur, Switzerland) following the protocol described in previous research (122). The depth of the countermovement was self-selected and players were asked to land close to the point of take-off. Two submaximal trials and two maximal CMJ were performed, with 1 min rest. The attempt with the highest jump height, based on the take-off velocity, was considered (CV = 3.5%). Raw data was exported and jump height, height and absolute peak power were calculated with Microsoft Excel (Microsoft Corporation, Redmond, WA, USA).

7.2.3.6. 10 m sprint

The 10 m sprint test, recommended for basketball players' assessment (9), was performed on the court with basketball shoes. Participants stood 0.3 m behind the starting line and, at investigator's signal, completed a maximal all-out straight line 10 m sprint, starting from a two-point stance. Time was measured with wireless photocells (WITTY System, Mircrogate, Bolzano, Italy) placed on the starting and finish lines, 1 m above ground level (5). Each player was allowed two trials, separated by 2 min rest (CV = 3.4%).

7.2.3.7. Change of direction test - T-test

The T-test was performed following the standard procedures described elsewhere (187). Since there is no external stimulus or decision-making skills, this test assesses COD speed. Time was measured with wireless photocells placed on the starting line, 1 m above ground level. Participants started the test on a two-point stance and were verbally encouraged throughout to perform maximal effort. The only parameter considered was total time. Two trials were allowed (CV = 1.5%), separated by 2 min, and the best time was considered.

7.2.3.8. Training protocols

The training protocols were performed two times per week and lasted 6 weeks. Both the OLT and MCT consisted of 3 exercises: half-squat, bench press and hip thrust. The characteristics of each program are presented in Table 1 and the weekly load progression in Table 2. The combination of 80% of 1RM + OL, applied in the MCT, was based on previous findings that reported that CT protocols with loads below 85% of 1RM seem to be the most effective in team-sports (174). The total number of sets and repetitions were the exact same for both training groups. On week 4, loads were adjusted during the first set of each exercise (half-squat and hip thrust on the first session of the week and bench press on the second), by estimating the 1RM based on barbell velocity, as previously described.

Table 1 - Characteristics of the training protocols

	Load	ICRI	Recovery
Modified Complex Training			
Half-Squat + Half-Squat (OL)	80% 1RM + OL	2 min 30 s	3 min
Bench Press + Bench Press (OL)	80% 1RM + OL	2 min 30 s	3 min
Hip Thrust + Hip Thrust (OL)	80% 1RM + OL	2 min 30 s	3 min
Optimal Load Training			
Half-Squat	OL	N/A	3 min
Bench Press	OL	N/A	3 min
Hip Thrust	OL	N/A	3 min

ICRI = intracomplex rest interval; OL = optimal load; 1RM = 1 repetition maximum; N/A = not applicable

Table 2 - Weekly progression of the training load

	Weeks 1-2		**Weeks 3**		**Week 4-5**		**Weeks 6**	
	Sets	Reps	Sets	Reps	Sets	Reps	Sets	Reps
Modified Complex Training								
Half-Squat + Half-Squat (OL)	3	3 + 4	3	3 + 5	4	3 + 4	3	3 + 4
Bench Press + Bench Press (OL)	3	3 + 4	3	3 + 5	4	3 + 4	3	3 + 4
Hip Thrust + Hip Thrust (OL)	3	3 + 4	3	3 + 5	4	3 + 4	3	3 + 4
Total	**9**	**21**	**9**	**24**	**12**	**21**	**9**	**21**
Repetition-Volume	189		216		252		189	
Optimal Load Training								
Half-Squat	3	7	3	8	4	7	3	7
Bench Press	3	7	3	8	4	7	3	7
Hip Thrust	3	7	3	8	4	7	3	7
Total	**9**	**21**	**9**	**24**	**12**	**21**	**9**	**21**
Repetition-Volume	189		216		252		189	

Reps = repetitions; OL = optimal load

7.2.4. Statistical analysis

Data are presented as mean ± SD. Descriptive statistics were calculated using SPSS 21.0 (IBM SPSS Inc., Chigaco, IL, USA). Normality was assessed with the Shapiro–Wilk test, the homogeneity of variances with the Levene test. To compare the effects of both experimental protocols, an ANCOVA test was performed in SPSS 21.0, with baseline values as covariates.

Pre-post ES were calculated using Cohen's equations (160). Between-group ES were determined by converting the partial eta-squared from the ANCOVA output to Cohen's d. Threshold values for ES statistics were: > 0.2 small, > 0.6 moderate, and > 1.2 large (188).

To make inferences about the true values of the effect on the selected variables, 90% CI were used. The likelihoods that the true value of the effect represented substantial changes (positive or negative) were calculated using a customized spreadsheet (189). For the between-group analysis, the same spreadsheet was used to convert the ANCOVA p-values and the effect statistic to magnitude-based inferences. An effect was considered unclear if its CI simultaneously overlapped the thresholds for positive and negative or if the chances of the effect being substantially positive and negative were both > 5% (188). Percentage change was derived from the log transformed data within the spreadsheet used for analysis.

To our knowledge, in basketball, there is no evidence of direct performance benefits or direct relationship between team and test performance on the tests performed in this study, as it occurs with other sports (190). Therefore, an effect was considered relevant when its ES ≥ 0.2, as suggested for team-sports (191).

For the variables in which a decrease in the mean represented a positive outcome (total time in T-test and 10 m sprint) the negative standardized change was multiplied by -1 for the graphic representation of the data, as it could be considered a positive effect. The qualitative terms and the default values were: most unlikely, < 0.5%; very unlikely, 0.5 - 4.9%; unlikely, 5 - 24.9%; possibly, 25 - 74.9%; likely, 75 - 94.9%; very likely, 95 - 99.5%; and most likely, > 99.5% (189).

7.3. RESULTS

Pre-post mean ± SD, percentage change in the mean and ESs for the OLT and MCT are shown in Table 3. Chances that each protocol presented a positive/trivial/negative effect and the respective inferences are displayed on Figure 1.

Regarding the OLT, *very likely* moderate improvements were observed for half-squat and hip thrust 1RM. *Likely* small improvements were attained for 10 m sprint and COD. For bench press, SLJ and CMJ peak power, *likely* trivial effects were found. Finally, for CMJ height, *possibly* trivial effects were observed. Considering the MCT protocol, *very likely* large adaptations occurred for hip thrust. *Likely* moderate effects were displayed for half-squat and COD; and *possibly* small effects for CMJ peak power and SLJ. *Possibly* trivial effects were obtained for bench press 1RM and CMJ height. For sprint, *unclear* effects were found.

Between-group analyses are shown in Figure 2. After controlling for baseline differences, all comparisons were deemed *unclear* except for SLJ, in which *likely* moderate ES favouring MCT were obtained.

Table 3. Body composition, strength and performance measurements for all variables on both experimental conditions

	Optimal Load Training				Modified Complex Training			
	PRE	POST	% Change (±90% CL)	ES (±90% CL)	PRE	POST	% Change (±90% CL)	ES (±90% CL)
Body Composition								
Muscle Mass (kg)	45.14 ± 5.22	46.04 ± 5.06	2.2 (±3.8)	0.16 (±0.37)	43.7 ± 6.6	42.6 ± 6.2	-2.3 (±5.6)	0.14 (±0.80)
8 Skinfold Sum (mm)	79.2 ± 21.6	75.4 ± 20.2	-4.4 (±8.0)	0.16 (±0.28)	79.5 ± 23.7	78.4 ± 21.0	-0.03 (±8.3)	0.04 (±0.09)
Body Fat (%)	12.3 ± 2.0	12.0 ± 1.8	-2.1 (±4.7)	0.13 (±0.23)	12.2 ± 1.8	12.08 ± 1.7	-1.1 (±1.9)	0.06 (±0.1)
Strength								
Half-Squat 1RM (kg)	149.1 ± 23.0	165.4 ± 27.9	10.8 (±5.3)	0.64 (±0.36)	154.8 ± 33.3	178.2 ± 14.5	17.2 (±11.6)	0.64 (±0.47)
Bench Press 1RM (kg)	76.4 ± 14.2	78.2 ± 15.0	2.2 (±3.7)	0.11 (±0.15)	66.6 ± 14.8	69.2 ± 13.2	4.3 (±4.6)	0.15 (±0.17)
Hip Thrust 1RM (kg)	144.2 ± 32.2	179.0 ± 46.4	23.4 (±17.7)	0.98 (±0.72)	145.7 ± 29.9	186.6 ± 39.6	28.2 (±19)	1.23 (±0.71)
Performance								
CMJ Height (cm)	36.5 ± 7.2	37.9 ± 7.5	4.0 (±3.8)	0.17 (±0.14)	36.4 ± 4.2	37.2 ± 3.6	2.2 (±4.3)	0.15 (±0.31)
CMJ Peak Power (W)	4699.1 ± 780.5	4833.1 ± 762.5	2.9 (±3.5)	0.16 (±0.11)	4594.2 ± 730.0	4775.3 ± 712.4	3.0 (±4.4)	0.22 (±0.21)
SLJ Distance (m)	2.27 ± 0.22	2.27 ± 0.24	-0.72 (±9.0)	0.01 (±0.2)	2.39 ± 0.23	2.46 ± 0.24	2.5 (±4.6)	0.27 (±0.24)
10m Sprint Time (s)	1.91 ± 0.09	1.87 ± 0.09	-1,63 (±1.6)	0.29 (±0.22)	1.89 ± 0.10	1.86 ± 0.13	-2.3 (±4.6)	0.27 (±0.56)
T-Test Time (s)	9.71 ± 0.67	9.46 ± 0.30	-3.03 (±3.2)	0.42 (±0.24)	9.45 ± 0.35	9.16. ± 0.50	-3.0 (±2.1)	0.75 (±0.6)

Data are shown as mean ± SD. OLT = Optimal Load Training; MCT = Modified Complex Training; ES = Effect Size; CL = Confidence Limits; RM = Repetition Maximum; CMJ = Countermovement Jump; SLJ = Standing Long Jump.

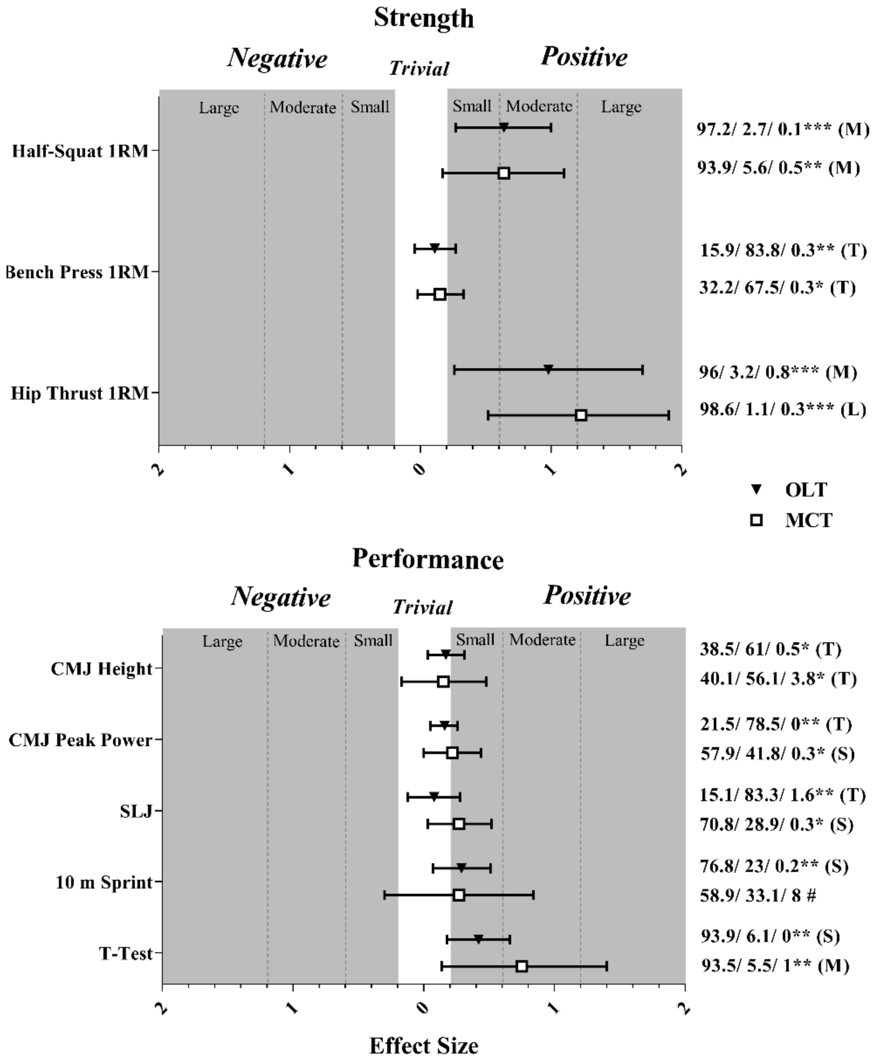

Figure 1. Changes in strength (A) and performance variables (B) in both training protocols. For the variables in which a decrease in the mean represented a positive outcome (total time in T-test and 10 m sprint) the negative standardized change (ES) was multiplied by -1 for the graphic representation of the data. The numbers represent the chance of the true value having positive/trivial/negative effect. T = trivial; S = small; M = moderate. #unclear; *possibly; **likely; ***very likely.

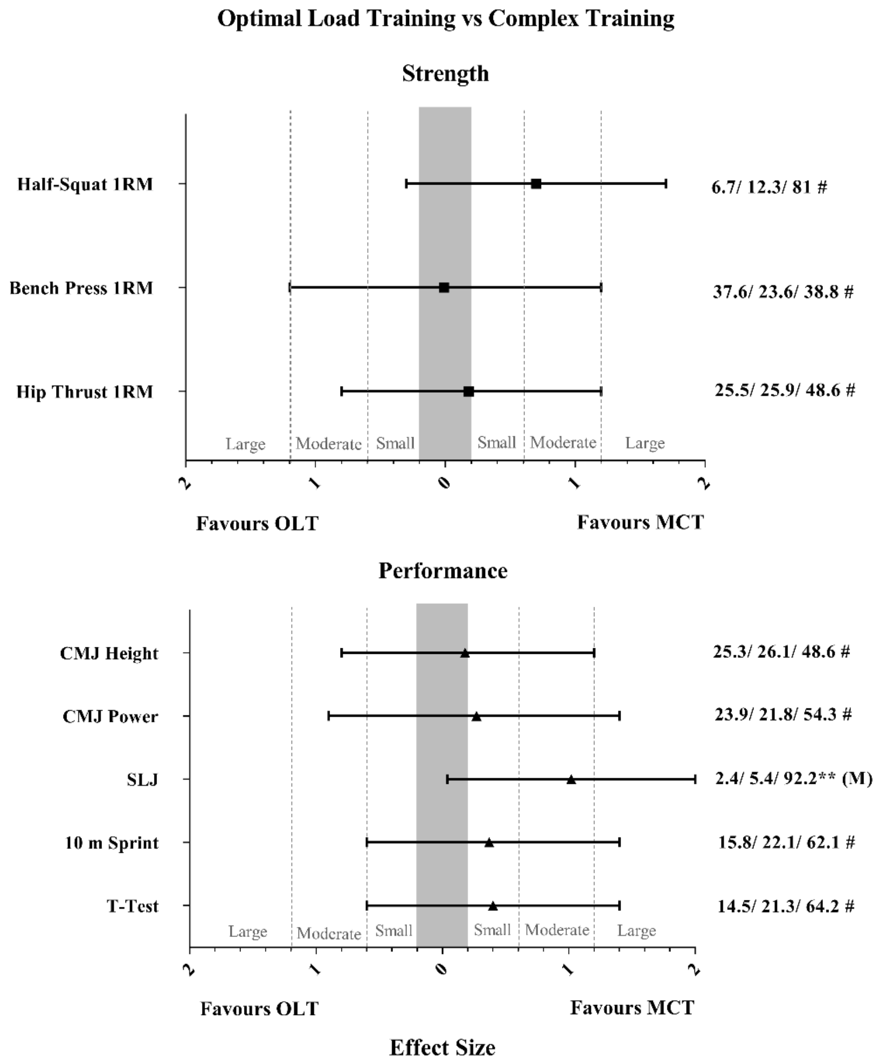

Figure 2. Optimal Load Training vs Modified Complex Training- Difference in the changes between protocols in strength (A) and performance variables (B), after controlling for baseline values. The numbers represent the chance that the true effect favoured OLT/ was trivial/ favoured MCT. The grey area represents trivial effects. M = moderate. #unclear; **likely.

7.4. DISCUSSION

The aims of this research were to investigate basketball players' strength and power adaptations following an OLT and a novel MCT intervention, and to compare their effects after a 6-week program. The main finding was that both protocols, performed alternatively with basketball training, increased lower-body strength in-season, without impairing the main neuromuscular performance variables (sprint, CMJ, SLJ and COD). This is very relevant for sport scientists and practitioners given that previous research has shown that significant strength losses occur in college-aged players during the course of a basketball season (59).

Concerning lower-body strength, both training groups displayed moderate-to-large improvements in half-squat and hip thrust 1RM, supporting previous research that reported dynamic strength gains in athletes following OLT (44, 175) or CT (70, 94, 96). Our data indicated increases of 17.2% and 10.8% for the MCT and OLT groups, respectively, in the half-squat exercise. The 17.2% improvement achieved by MCT group may be explained by the fact that the players in this program completed 3 of the 7 total reps in each set with 80% of 1RM, hence lifting heavier loads each session (greater volume of higher intensity loads). Concerning the OLT group, athletes were able to achieve a higher acceleration of the barbell for all repetitions, therefore applying a considerable amount of force (force equals mass multiplied by acceleration), which may account for the strength gains (44).

It has been recommended that training for maintaining or increasing strength throughout the season is important for basketball players (10). Moreover, a review by Suchomel et al. (47) concluded that greater muscular strength is associated with enhanced general sport skill performance and to a greater robustness and reduced risk of injury, which highlights the practical relevance of the present findings.

Regarding upper-body strength, bench press 1RM was not substantially affected in either group, as demonstrated by the trivial ES obtained with increases of 2.2% in OLT and 4.3% in MCT. This finding is in contrast with Sarabia et al. (192) that investigated the effects of an OLT and a traditional power training (50% of the maximum number of possible repetitions) in recreationally active participants and reported significant increases in bench press 1RM of 10.6% and 14.5%, respectively. However, a direct comparison among results is difficult due to the differences in the training programs, the duration of intervention and sample characteristics. Interestingly, we found positive meaningful effects for lower-body strength but not for upper-body. Two lower limbs exercises were performed, while only one was prescribed for upper-body, suggesting that the training volume for the upper-body was too low to generate adaptations in athletes with previous experience in bench press (193), such as basketball players. We can hypothesize that applying the same stimulus (same repetition and loading scheme) for all exercises and muscle groups was not appropriate to elicit positive adaptations in both upper- and lower-body.

Concerning VJ ability, both protocols attained trivial effects in CMJ. In light of the results reported on the meta-analysis by Freitas et al. (174), an increase CMJ height could be expected following MCT, which did not occur. The absence of jumping/plyometric exercises during the intervention may have hindered specific adaptations in the high-velocity zone of the force-velocity relationship (194). Loturco et al. (44) reported a 11.5% increase in CMJ height following a OLT intervention with elite soccer players whereas, in our study, a 4% increment was obtained for the OLT group. The substantial differences between programs may account for such disparities. First, Loturco et al.'s (44) soccer players completed 18 sessions during the intermission period (no official games were played) whereas, in the present study, players completed 12 sessions, in-season. Second, in Loturco et al. (44) study, players performed jump squats instead of half-squat and hip thrust. Jump squat has been shown to be more connected to jump abilities in team-sports athletes than half-squat, since there is no breaking phase in the former exercise (194).

Given that the basketball players in this research had previous experience in strength/power training, a plateau effect might have been achieved prior to the intervention. This advocates that the training stimulus was not appropriate to elicit relevant adaptations in CMJ and that there was a reduced transfer between the strength gains observed and VJ performance. To maximize the transference of power training to performance, training must include movement patterns, loads and velocities that are specific to the demands of the sport (195), which was not the case in this study.

Regarding SLJ, a moderate ES favouring the MCT group was observed (Figure 2). This greater effect may be explained by the large strength gains in the hip thrust exercise in which there is a notable application of horizontal force (185), similarly to the SLJ.

Sprint performance was *likely* positively affected in the OLT group but the effects of the MCT protocol were *unclear*. The MCT showed a 58.9% chance of having a positive effect on sprint, but also an 8% likelihood of having a negative impact. In the present research, small ES were obtained for a distance of 10 m for OLT and MCT, with the latter group presenting a substantially wider CI. Freitas et al.'s (174) meta-analysis reported a moderate increase on sprint performance (ES = 0.73) following CT interventions in team-sports athletes, over distances between 15 and 30 m. However, in the studies included, CT incorporated plyometric or ballistic exercises, allowing greater movement velocities to be achieved in the complex pairs, as a result of the absence of a braking phase (194).

It is important to highlight that ours is the first research to investigate the effects of a MCT protocol in which the complex pairs consisted on the same exercise performed with a moderate and an optimal load. It may be that this type of loading is not as effective as the traditional CT initially proposed by Ebben (76), that utilized higher velocity exercises (e.g., CMJ, short sprints, medicine ball throws, etc). In addition, our intervention was applied during the competitive phase of the season and a ceiling effect may have been previously reached by the athletes (96). Therefore, in the absence of specific sprint or acceleration training in both protocols, only small effects were achieved. Regarding OLT, Loturco et al. (44) reported a significant improvement (7.1%) in 10 m sprint performance following a 6-week intervention period, while our study only obtained an increase of 1.6%. As stated before, the dissimilarities between programs may help explain the higher increments reported elsewhere (44, 174).

COD ability, measured with the T-test, was *likely* positively affected following both protocols. This finding supports previous research regarding OLT (44) but is in contrast with most literature on CT, which found no relevant effects on COD performance in team-sports (70, 94, 96). Interestingly, large effects on hip thrust 1RM and small on SLJ were achieved in MCT, and moderate and trivial were displayed in the OLT group on the same exercises, characterized by a prominent application of horizontal force (185). In the T-test, the distances covered are short and several COD are performed. Hence, the ability to accelerate and decelerate plays an important role. Given that in accelerated running, the application of horizontal forces is crucial (196), the improvements observed in SLJ distance and hip thrust 1RM may account for the results attained.

Moreover, it has been suggested that increases in maximal strength are more likely to increase sprint performance at short distances (5 m) (197), when acceleration plays the most important role, as it occurs in the T-test. Nevertheless, more research is warranted on COD ability. Finally, regarding body composition, trivial effects were obtained in both training groups, indicating that no changes were observed in body fat or muscle mass during the intervention period.

When comparing the effects of the two interventions, it was *unclear* which program resulted in higher adaptations. This outcome suggests that the measures used were not sensitive enough to detect a clear effect with the sample size analysed. Concerning OLT, different studies comparing this method to traditional strength training interventions found similar results (44, 108). No differences were reported between training protocols in the relative changes in back squat 1RM, CMJ and 20 m sprint (108) or COD speed in soccer players (44). With respect to CT, Brito et al. (94) found it was equally effective in increasing muscular strength and sprint performance when compared to traditional resistance training. The overall similar adaptations following OLT and MCT may be due the high neuromuscular demand of both protocols along with the intention of moving the loads as fast as possible in every workout session. However, we cannot exclude that the basketball training/competition stimulus may have contributed to the observed adaptations.

Some limitations need to be addressed. Firstly, the small sample size prevented us from identifying clear between-group effects, as shown by the large CIs. Secondly, as no CG was present, it was not possible to determine the influence of the basketball training sessions on the adaptations reported. We can only conclude that the training interventions combined with the basketball-specific stimulus led to these outcomes. Finally, adaptations to CT programs have been suggested to be highly individualized (174) but, in the present research, the ICRI and the intensity of the CA were similar to all players because it would not be practical, in a team-sports setting, to individually adjust rest periods. Nevertheless, training was individualized in the sense that all players trained within their own specific optimal power zone in both OLT and MCT. Despite these limitations, it is worth noting that this study was delivered in a real sporting setting, where athletes perform several concurrent activities, and within the constraints of limited time and resources, typical in this type of applied research (198).

7.5. CONCLUSIONS AND PRACTICAL APPLICATIONS

In conclusion, this study investigated the effects of two different resistance training protocols aimed at developing strength and power. Similar adaptations were achieved following OLT and MCT in basketball players. Strength gains obtained were moderate-to-large for lower-body exercises but trivial for upper-body. Athletes in the OLT group achieved relevant improvements in sprint and COD and players in the MCT group increased SLJ and COD performance. The small effects on sprint and SLJ and the trivial in CMJ suggest that there was a reduced transfer between the intervention programs and the performance variables.

According to our results, OLT and MCT training programs may be prescribed during the competitive phase of the season to increase strength in basketball players without the use of heavy loads (> 85% 1RM) and without impairing the main neuromuscular performance variables (i.e., sprint, CMJ, SLJ and COD). The similar adaptations between OLT and MCT indicate that basketball sport scientists and S&C professionals may use either method to counteract possible strength losses during the season.

VIII – SUMMARY AND DISCUSSION OF RESULTS

VIII. SUMMARY AND DISCUSSION OF RESULTS

The main objective of the present compendium of studies was to investigate the acute and short-term effects of different strength and power-oriented resistance training programs on neuromuscular performance variables such as maximal dynamic strength, mechanical power output, sprint, vertical and horizontal jump and COD ability in basketball players during the in-season period. Results indicated that (I) HRC induced significantly greater fatigue levels than PCT, which negatively affected physical and technical performance of basketball players; (II) CT is an effective training method to develop sprint and VJ performance in team-sports, making it a suitable alternative to be used by S&C coaches and (III) a modified CT and OLT resulted in increments in lower-body maximal dynamic strength without impairing important neuromuscular performance variables such as VJ, sprint or COD speed, in-season.

In Study 1 (199), the objective was to examine the acute effects of two circuit-based training protocols (i.e., HRC, 6RM; PCT, 45% of 1RM) on CMJ and SLJ performance, shooting accuracy, RSA, COD, upper-body power output and RPE. As expected, based on previous research that described maximal strength training as being more demanding than power training using 40% 1RM (116), HRC resulted in greater fatigue levels and performance decrements than PCT. Of note, this study is line with a recent investigation with soccer players that showed that HRC generated greater aerobic and metabolic stress than traditional strength training, resulting in higher heart rate during and after an acute session, increased blood lactate concentration, relative energy cost and excess post-exercise oxygen consumption (38).

From an applied perspective, understanding the effects of resistance training-induced fatigue is important for basketball S&C professionals and sports scientists because such type of training is performed concurrently with practice sessions and matches throughout the season (15, 16). According to Calleja-González et al. (24), to ensure adequate recovery and optimal adaptations, it is necessary to know the type of induced fatigue and its underlying mechanisms, whether they are caused by competition load or complementary training programs. The experimental design and methodological approach employed in Study 1 (199) allowed identifying the existence of post-HRC fatigue, as shown by several performance-based indicators such as impaired jump, sprint, RSA and COD ability (28, 200) or decreased shooting accuracy (42, 121), but not its specific mechanisms (i.e., if central or peripheral). It was hypothesized that the fatigue induced by the HRC was peripheral in origin, which was indeed confirmed in a later study (34). In the mentioned investigation, the twitch interpolation technique was used to assess the neuromuscular function of the knee extensors after an acute bout of HRC and results yielded a reduction in the maximum voluntary contraction and resting potentiated twitch amplitude, but not in voluntary activation (34). Therefore, it was concluded that the fatigue mechanism most prevalent following HRC was peripheral in origin. Considering that this fatigue mechanism is also associated with intermittent-sprint exercise (32, 201) or repeated COD tasks in basketballers (202), HRC should be used with caution during congested periods of the season.

Remarkably, a novel finding from Study 1 (199) was that the PCT, contrary to HRC, did not negatively affect any physical or technical outcomes when compared to REST conditions. For the S&C and basketball coaches, this has important practical applications. Firstly, it seems that power-based training protocols may be used during the in-season period, before a basketball practice or competitive match, as it does not induce neuromuscular fatigue, thus allowing for faster recovery processes (24, 28) and a reduced risk of injury (5, 23). Secondly, if the aim of a specific basketball session is to develop or perfect technical skills under fatiguing conditions or if the S&C coach wants to provide an extra and complementary cardiorespiratory stimulus (38) for players with less playing minutes while also developing/maintaining strength and power (38, 60), HRC may be a suitable and time efficient option.

However, the fact that HRC is significantly more demanding than power circuit-based or traditional strength training protocols (34, 38, 66) questions its applicability, in-season, with players with greater playing time, where match-induced fatigue is superior (23). In this respect, and taking into consideration that maintaining strength and power levels throughout the season is crucial in basketball (10, 203), coaches are recommended to utilize alternative methodologies. Therefore, as part of the present research, it was intended to bring further understanding regarding the application of other commonly used protocols to develop both strength and power such as the CT and OLT.

Particularly, in Study 2 (174) the main objective was to systematically review the literature and perform a meta-analysis on the effectiveness of CT interventions to improve sprint and VJ ability in team-sports. Furthermore, moderating factors (i.e., athletes' and interventions' characteristics) potentially explaining or contributing to positive adaptations following CT were analyzed to provide practical guidelines to S&C coaches and sports scientists on how to design an adequate, evidence-based CT program. Based on the data extracted from the scientific literature, it was concluded that CT elicits positive medium and small effects on sprint and VJ performance, respectively. These results have since been supported by another recently published meta-analysis (204) and by unpublished data (currently under review) from our research group that, in addition, reported that CT interventions also increase maximal dynamic strength and COD ability in team-sports athletes.

Interestingly, an unprecedented finding from the subgroup analysis conducted in Study 2 (174) was that, in team-sports, utilizing CA with intensities < 85% of 1RM (within CT protocols) seems to promote greater adaptations than utilizing heavy loads. To some extent, these results could be explained by PAP moderating factors. According to Seitz and Haff (78) PAP responses are modulated by strength levels and weaker individuals (e.g., team-sports athletes when compared to weightlifters (111)) potentiate to a greater extent with submaximal loads, probably because heavy resistances affect the fatigue-PAP balance in favor of fatigue (77). Therefore, S&C coaches are advised to use loads no greater to 85% of 1RM in the CA when working on a team-sports setting to maximize sprint and VJ capabilities. Furthermore, the subgroup analysis displayed that ICRI longer than 2 min are recommended. As a consequence, protocols as the ones utilized by Faude et al. (96) or Cavaco et al. (73) in which intervals shorter than 2 min were used and sprint performance did not improve, are potentially not the most effective. Also worth noting, on the context of the present thesis, was that players from jump-predominant sports, such as basketball, seem to benefit the most from CT interventions, further supporting the utilization of this methodology with basketballers.

The duration of the training program was also identified as an important moderating factor. Notably, this finding seems to be consistent across different training methods in the field of S&C as other studies with completely dissimilar types of intervention concluded that longer interventions induce greater benefits in, for example, sprint performance (137, 205). Concerning CT, 6 or more weeks may be a good reference for S&C professionals in terms of program duration.

According to the results of Study 2 (174) and those from posterior CT investigations reporting positive effects on performance variables in team-sports (70, 97-99), there seems to be compelling evidence supporting this method as an appropriate option to develop athletic performance. However, the results from the meta-analysis were inconclusive as to how CT-induced adaptations on maximal strength, sprint, jump and COD capabilities compared to other methods since the CT interventions were only compared to control participants. Specifically, after the completion of the second study of the present thesis, it remained unknown if CT was more effective, for instance, than a training program utilizing loads that maximized power outputs in every exercise of the workout. Given that increments in maximal dynamic strength, sprint and jump ability had been previously reported following OLT (44, 108, 175), it was considered relevant to try to fill this gap in the scientific literature.

Consequently, in Study 3 (206) the objective was to investigate the effects on basketball players' neuromuscular performance of an OLT and a novel modified CT, designed according to the findings of Study 2 (174) and with the unique feature of having the same exercise performed with a moderate (80% of 1RM) and an individually determined OL. The main discovery indicated that both protocols increased lower-body strength during the competitive phase of the season, without negatively affecting the main neuromuscular performance variables (i.e., sprint, CMJ, SLJ and COD). This is very relevant for sport scientists and practitioners as it highlights that OLT and MCT performed with moderate and optimal loads may counteract possible strength losses that have been reported to occur during the course of a basketball season (59). Most importantly, such increments in maximal dynamic strength were achieved without using heavy loads. It is essential to keep in mind that maximal strength loading (i.e., heavy resistances) generates significantly higher fatigue than moderate, explosive loads (116, 199), which may be problematic, as greater fatigue levels are associated with an increased risk of injury in basketball players (5, 23). Therefore, MCT and OLT seem to be effective alternatives to programs such as the HRC that have been found to improve strength but that utilize heavier loads (38, 60) and induce greater metabolic stress (34, 38).

At first glance, the trivial-to-small meaningful improvements in sprint, CMJ, SLJ and COD ability suggest that there was a reduced transfer between the MCT and OLT interventions and the performance variables. The limited transference may be related to the fact that no plyometric exercises were performed in either protocol. The mechanical differences between exercises in which accelerative forces are applied throughout the entire concentric portion of the lift (e.g., jump squat) and others in which a deceleration occurs during the final stages of the concentric phase of the exercise (e.g., half-squat) (194), potentially explain why using solely the half-squat might have limited increases in performance. Briefly, the existence of a braking phase in this lift may have hindered velocity-specific adaptations that would have contributed to increments in explosive actions such as sprinting or jumping (113).

Nonetheless, three aspects are worth considering here. Firstly, in sports such as basketball, in which a substantial number of accelerations, decelerations and high-impact jumping actions are performed during practice and competition (1, 3), the volume of plyometric training greatly decreases during the in-season period, as reported by NBA S&C coaches (15), possibly to reduce joint loading. Thus, the MCT and OLT protocols proposed on Study 3 (206), that incorporated no plyometric exercises, closely resemble the characteristics of the programs used by S&C professionals on a daily basis and on an applied basketball setting. Secondly, despite not incorporating plyometric drills, no protocol impaired sprint, jump or COD abilities, confirming the potential for MCT and OLT to be implemented during the season with seemingly no negative consequences on basketball players' neuromuscular performance. Finally, responses to CT have been shown to be highly individualized (82, 101) and it cannot be excluded that a more individually adapted protocol for each player would have possibly been more effective on improving the abovementioned neuromuscular performance outcomes.

In summary, from a practical and applied perspective based on the results of the present compendium of studies, basketball S&C coaches and sport scientists should be aware that using heavy loads in a circuit-based resistance training (i.e., HRC) is significantly more demanding and fatigue-inducing than utilizing moderate loads (i.e., PCT). Therefore, considering the recovery needs of the players, alternative resistance training methods may be more appropriate to increase/maintain strength and neuromuscular performance during the in-season period. For example, CT was found to be an effective method to enhance sprint and VJ ability, particularly when interventions longer than 6 weeks with loads no greater than 85% of 1RM and 2 min of ICRI were prescribed. Finally, a modified CT and an OLT protocol in which moderate loads and no plyometric drills were performed, resulted in similar increases in lower-body maximal dynamic strength without impairing sprint, vertical and horizontal jump performance and COD ability during the competitive period. As such, when following a periodized strength training approach, MCT and OLT are two methods that can be used throughout the season to offer variability to the resistance training sessions possibly contributing to help keep players engaged and motivated in the weight room while HRC should be considered mainly during the pre-season or off-season period.

IX – CONCLUSIONS

IX. CONCLUSIONS

9.1. GENERAL CONCLUSIONS

The results of the present compendium of articles allowed concluding that HRC resulted in greater fatigue levels and higher acute physical and technical performance decrements in basketball players, in-season, when compared to PCT, hence questioning its applicability during match-congested periods over the course of the competitive phase of the season. Moreover, through the systematic review and meta-analysis, it was concluded that CT can be an effective method to increase sprint and VJ performance in a team-sports setting. Finally, in contrast with what had been initially hypothesized, it was concluded that the CT and OLT 6-week interventions did not result in meaningful increases in all strength and neuromuscular performance variables (i.e., vertical and horizontal jump, sprint and COD) in basketball players, in-season.

9.2. SPECIFIC CONCLUSIONS

The specific conclusions of the studies comprising the present thesis are displayed below. Importantly, the following conclusions are only applicable to athletes with similar characteristics to those presented in each investigation.

Study 1:

- HRC, but not PCT, resulted in acute vertical and horizontal jump performance impairments in semi-professional basketball players.
- HRC, but not PCT, resulted in acute declines in repeated sprint and COD ability in semi-professional basketballers.
- HRC, but not PCT, led to acute decreases in semi-professional basketball players’ 3-point shooting accuracy.
- HRC, but not PCT, negatively affected acute upper-body power production in semi-professional basketballers.

- HRC was perceived as more intense than PCT.

Study 2:

- The systematic review of the scientific literature and the meta-analysis performed on the application of CT in a team-sports setting yielded that this method is effective in increasing sprint and VJ performance.

- CA with loads below 85% of 1RM, interventions lasting 6 or more weeks and ICRIs longer than 2 min were identified as possible moderating factors contributing to positive adaptations on sprint and VJ ability following CT programs in team-sports athletes. In addition, jump-predominant modalities were found to benefit more from this training methodology.

Study 3:

- Athletes in both the OLT and MCT programs improved COD ability after 6 weeks of intervention. Furthermore, in the OLT group positive adaptations in sprint performance were observed whereas in the MCT group improvements were obtained in horizontal jump ability. However, contrary to the initial hypothesis, none of the protocols contributed to increments in VJ performance of semi-professional basketball players, in-season.

- Players in the OLT and MCT groups displayed lower-body maximal dynamic strength gains, during the competitive phase of the season. Regarding upper-body strength, no positive adaptations were observed in either group.

- The basketball players' body composition was not affect following the OLT and MCT interventions.

- After 6 weeks of intervention, athletes in both training groups (i.e., OLT and MCT) achieved similar adaptations on vertical and horizontal jump performance, sprint and COD ability. However, in contrast with what had been initially hypothesized, CT did not produce greater maximal dynamic strength gains when compared to OLT as unclear between-group differences were obtained in this particular outcome.

X – LIMITATIONS

X. LIMITATIONS

Some limitations of the studies composing the present thesis must be addressed:

- The small sample sizes in Study 1 and Study 3 may have prevented the identification of significant and meaningful differences between groups, mainly in the latter research.

- In Study 1, the last assessment was completed more than 30 min after the end of the HRC and PCT sessions and all tests were performed in sequence, which may have affected the results. The long recovery period between some tests and the end of the training protocols, as well as the influence that one test may have had on the subsequent one, must not be disregarded.

- The loads used in the PCT protocol, in Study 1, were not individually determined for each athlete in each exercise. Therefore, as all players worked with a load corresponding to 45% of 1RM in every exercise, it is possible that the stimulus imposed by that load was not similar for every participant (i.e., 45% of 1RM might have been the load that maximized power output in a specific exercise for one athlete but not for the other).

- The small number of papers included in Study 2, due to the few existing publications in the literature that attempt to study the effects of CT interventions in team-sports, may have skewed the conclusions obtained. Consequently, caution is necessary when generalizing the results found herein.

- The high heterogeneity in athletes' characteristics and CT protocols in Study 2 made comparison between studies difficult, probably affecting the outcomes reported. In addition, the training loads outside the CT interventions were not considered in the analysis, neither were the resistance training protocols performed in the weeks prior to the CT protocols.

- The absence of a CG in Study 3 made it impossible to determine the actual influence of the basketball training and competition on the adaptations obtained.

XI – PRACTICAL APPLICATIONS

XI. PRACTICAL APPLICATIONS

From an applied and practical perspective, according to the results from the studies in the present thesis, basketball S&C coaches and sport scientists should consider that:

- A circuit-based resistance training protocol performed with heavy loads (i.e., HRC) was found to be more demanding and fatigue-inducing than a moderate load power-oriented circuit training (i.e., PCT). Therefore, HRC is potentially more suitable to be applied in the off-season and/or pre-season periods or when the objective of the basketball on-court session is to develop or perfect technical skills under fatiguing conditions.

- In alternative, from a fatigue-management perspective, PCT or other training methods such as CT or OLT appear to be more appropriate to be used during the competitive phase of season to develop/maintain lower-body strength and neuromuscular performance (i.e., vertical and horizontal jump, sprint and COD).

- CT was identified as an effective method to enhance sprint and VJ ability in team-sports athletes. The meta-analysis conducted on the published scientific literature yielded that interventions longer than 6 weeks with loads no greater than 85% of 1RM and 2 min of ICRI seem to be the most adequate in this population.

- A modified CT and an OLT protocol in which moderate loads were used and no plyometric drills were performed, resulted in similar increases in lower-body maximal dynamic strength without impairing sprint, vertical and horizontal jump performance and COD ability during the competitive period. Thus, both methods can be used in-season to offer variability to the resistance training sessions possibly contributing to help keep players engaged and motivated in the weight room.

XII – FUTURE RESEARCH LINES

XII. FUTURE RESEARCH LINES

After the completion of the present thesis, future research lines arise from the results obtained. In this regard, potential future investigations that could bring further understanding on the topics studied herein are presented below:

- To investigate the residual fatigue and time-course recovery profile following an acute bout of HRC to determine the time point when neuromuscular and technical performance variables return to baseline levels (e.g., post-6h, post-24h, post-48h).

- To investigate complementary neuromuscular adaptations following the different training methods studied in the present thesis by assessing variables such as RFD, muscle activation (electromyographic activity) or by analyzing the reflex activity of the spinal cord (H-reflex) as an indicator of the excitability of the spinal cord α-motoneurons.

- To research the effects of CT programs with individually determined intervention characteristics (i.e., CA intensity, ICRI) according to individual PAP responses.

- To determine the effectiveness of a circuit CT protocol in which lower- and upper-body complex pairs would be performed alternatively during each of the ICRI (e.g. a set of bench press performed during the ICRI between a half-squat and a CMJ). A potentially more time-efficient training scheme could arise from re-arranging the exercise order by alternating muscle groups with the aim of optimizing the utilization of the rest intervals.

- To investigate the effects of different long-term periodized strength training approaches combining the training methods studied herein (e.g., over the course of a complete basketball season) on strength and neuromuscular performance. In the present thesis, the effects of a 6-week CT or OLT program were studied but no evidence was obtained regarding the effects of performing, for instance, a HRC intervention during the pre-season followed by a CT protocol and then an OLT program during the in-season period.

- To determine the potential of HRC, PCT, CT or OLT as "priming" or "morning exercise" strategies in basketball players, in-season.

XIII – MENCIÓN INTERNACIONAL

XIII. MENCIÓN INTERNACIONAL

Con el objetivo de cumplir con los criterios especificados en el Real Decreto 99/2011 para la obtención de la Mención Internacional en el Título de Doctor, se presentan las conclusiones del presente compendio de estudios en un idioma distinto al utilizado en la restante tesis.

13.1. CONCLUSIONES GENERALES

Los resultados del presente compendio de artículos permitieron concluir que el entrenamiento HRC produjo mayores niveles de fatiga y un descenso agudo del rendimiento físico y técnico en los jugadores de baloncesto, en el periodo competitivo, en comparación con el PCT, por lo que se cuestiona su aplicabilidad en los períodos más congestionados de la temporada. Además, a través de la revisión sistemática y el meta-análisis, se concluyó que el CT puede ser un método eficaz para aumentar el rendimiento de sprint y salto vertical en deportes de equipo. Además, contrariamente a la hipótesis inicial, se concluyó que las intervenciones de CT y OLT de 6 semanas de duración no produjeron aumentos significativos en todas las variables de fuerza y rendimiento neuromuscular (es decir, salto vertical y horizontal, sprint y COD) en los jugadores de baloncesto durante la fase competitiva de la temporada.

13.2. CONCLUSIONES ESPECÍFICAS

A continuación, se presentan las conclusiones específicas de cada uno de los estudios que componen la presente tesis. Es importante destacar que las siguientes conclusiones solo son aplicables a atletas con características similares a las presentadas en cada investigación.

Estudio 1:

- El programa HRC, pero no el PCT, produjo descensos agudos en el rendimiento en salto vertical y horizontal en jugadores de baloncesto semi-profesionales.
- El entrenamiento HRC, pero no el PCT, disminuyó de forma aguda la capacidad de sprint repetido y la capacidad de cambio de dirección en jugadores de baloncesto semi-profesionales.
- El protocolo HRC, pero no el PCT, produjo una disminución aguda en la precisión de tiro de 3 puntos en jugadores semi-profesionales de baloncesto.
- El programa HRC, pero no PCT, afectó negativamente la producción aguda de potencia del tren superior en jugadores de baloncesto semi-profesionales.
- El entrenamiento HRC fue percibido como más intenso que el protocolo PCT.

Estudio 2:

- Tras la revisión sistemática con meta-análisis realizada, se concluyó que CT es un método eficaz para mejorar el rendimiento en el sprint y el salto vertical en atletas de deportes de equipo.
- Las actividades condicionales con cargas por debajo del 85% del 1RM, las intervenciones de 6 semanas o más y los ICRI de más de 2 min, se identificaron como posibles factores moderadores que contribuyen a las adaptaciones positivas en la capacidad de sprint y salto vertical tras programas de CT en atletas de deportes de equipo. Además, se observó que las modalidades de predominancia de salto (e.g. baloncesto) se benefician más de esta metodología de entrenamiento.

Estudio 3:

- Los jugadores de baloncesto semi-profesionales en los programas OLT y MCT mejoraron la capacidad de cambio de dirección después de 6 semanas de intervención. Además, en el grupo OLT se observaron adaptaciones positivas en el rendimiento del sprint, mientras que en el grupo MCT se obtuvieron mejoras en la capacidad de salto horizontal. Sin embargo, contrariamente a la hipótesis inicial, no se observaron incrementos en la capacidad de salto vertical de los jugadores de baloncesto semi-profesionales, en temporada, tras los protocolos MCT y OLT.

- Los jugadores en los grupos OLT y MCT mostraron ganancias de fuerza dinámica máxima en el tren inferior, durante la fase competitiva de la temporada. Con respecto a la fuerza del tren superior, no se observaron adaptaciones positivas en ninguno de los grupos.

- No se registraron cambios a nivel de la composición corporal de los jugadores de baloncesto después de las intervenciones OLT y MCT.

- Después de 6 semanas de intervención, los atletas en ambos grupos de entrenamiento (es decir, OLT y MCT) lograron adaptaciones similares en la capacidad de salto vertical y horizontal, el sprint y el cambio de dirección. Sin embargo, en contraste con la hipótesis inicial, el programa MCT no produjo mayores ganancias en la fuerza dinámica máxima en comparación con el OLT, ya que no hubo diferencias entre los grupos en esta variable.

XIV – REFERENCES

XIV. REFERENCES

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XV. APPENDICES

APPENDIX 1. Study 1: ACUTE EFFECTS OF TWO DIFFERENT RESISTANCE CIRCUIT TRAINING PROTOCOLS ON PERFORMANCE AND PERCEIVED EXERTION IN SEMI-PROFESSIONAL BASKETBALL PLAYERS

Reference:

Freitas TT, Calleja-González J, Alarcón F, Alcaraz PE. Acute effects of two different resistance circuit training protocols on performance and perceived exertion in semiprofessional basketball players. J Strength Cond Res. 2016;30(2):407-14.

ACUTE EFFECTS OF TWO DIFFERENT RESISTANCE CIRCUIT TRAINING PROTOCOLS ON PERFORMANCE AND PERCEIVED EXERTION IN SEMIPROFESSIONAL BASKETBALL PLAYERS

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ABSTRACT

Freitas, TT, Calleja-González, J, Alarcón, F, and Alcaraz, PE. Acute effects of two different resistance circuit training protocols on performance and perceived exertion in semiprofessional basketball players. *J Strength Cond Res* 30(2): 407–414, 2016—This study aimed to investigate the acute effects of two different resistance circuit training protocols on basketball players' physical and technical performance and rating of perceived exertion (RPE). In a repeated-measures, crossover experimental design, 9 semiprofessional basketball players performed a Power Circuit Training (PCT; 45% 1RM) and a High-Resistance Circuit Training (HRC; 6RM), on consecutive weeks. Vertical and horizontal jump performance, 3-points shooting accuracy, repeated-sprint ability (RSA), agility, and upper body power output were measured before and after training. The RPE was assessed 20 minutes after resistance training. One-way repeated-measures analysis of variance showed performance decrements in vertical jump height and peak power, horizontal jump distance, 3-points percentage, bench-press power output, RSA total and ideal time, and agility T-Test at total time following HRC, but not PCT ($p \leq 0.05$). The RPE was higher in HRC compared with PCT. The results of this study indicated that HRC was perceived as being harder and produced higher fatigue levels, which in turn lowered acute performance. However, low-to-moderate intensity loads did not negatively affect performance. Thus, completing a PCT session may be the most appropriate option before a practice or game as it avoids acute–resistance–training-induced performance decrements. However, if the objective of the basketball session is to develop or perfect technical skills during fatiguing conditions, HRC may be the more suitable option.

KEY WORDS power, strength, basketball, repeated-sprint ability, vertical jump, shooting

INTRODUCTION

Basketball is a sport characterized by its intermittent, high-intensity activity that requires players to perform actions such as: jumping, sprinting, shuffling, or changing directions (1,26). Increased vertical jump ability (9,43), repeated-sprint ability (RSA), (5,38) and agility (9,43) are important determinants of high performance in basketball. Hence, strength and conditioning is a vital component in this sport and focuses on enhancing aerobic capacity, agility, speed, strength, and power (35). In fact, the ability to generate power and explosive force is essential for athletic performance (11).

Overall, both heavy-resistance training and power training using light-to-moderate loads are executed to improve athletic performance in team sports during the season (3,16,35). On the one hand, heavy-resistance training increases maximal strength (11), which is considered the physical quality that most affects maximal power (7). On the other hand, power training not only increases maximal power outputs using lighter loads and maximal movement velocities but also triggers specific neuromuscular adaptations that result in performance enhancements (7,11,24). The total work, duration of activation, and fatigue levels with power training are generally lower compared to heavy-resistance training (20).

Fatigue after resistance training has been widely studied (17,20,31). Fatigue is a complex, task-dependent phenomenon (12) that is defined as an exercise-induced reduction in the ability to exert muscle force or power (14) or, more globally, as an exercise-induced decline in athletic performance (19). It may occur because of changes at the muscular level

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30(2)/407–414

Journal of Strength and Conditioning Research

(peripheral fatigue) and of failure of the central nervous system to adequately drive the motor neurons (central fatigue) (12,14). Regarding athletic performance, time increments in sprint, agility, or RSA tests could be interpreted as manifestations of fatigue. In addition, fatigue may also manifest itself as a decrement in technical execution or in the motor skill outcome, which can be measured as ball velocity or accuracy (19,21).

Understanding the acute effects of postresistance training fatigue on performance of basketball players' is crucial since, during the competitive season, moderate- and high-intensity resistance training sessions are performed (22,35). To our knowledge, only 1 study (41) has investigated the acute effects of strength training in basketball players' performance by analyzing vertical jump, anaerobic power, and shooting accuracy after moderate-intensity resistance training. The results obtained indicated that such training, when completed 6 hours before a basketball practice, had no negative effects on performance. However, some semiprofessional teams or teams that must travel regularly between games may not have the opportunity to perform strength training in the morning and a basketball practice in the afternoon. Therefore, these two training components are generally executed in sequence. Nonetheless, there exists a lack of research addressing the acute effects that strength/power training may have on players' specific physical and technical performance due to postresistance training fatigue. In fact, no research has been conducted with heavy-resistance and power training that have been completed immediately before a regular basketball practice, and for that reason, their effects on basketball players are still unknown.

Therefore, the main aim of this study was to investigate the acute effects of two different resistance training protocols on the main factors of high performance in basketball. We hypothesized that power training would result in less perceived exertion than heavy-resistance training and would also result in lower declines on performance on vertical and horizontal jumps, shooting accuracy, agility, RSA, and upper body power output. The results may have important implications when determining the objective of the in-court basketball practice, if a strength session is performed immediately before it.

METHODS

Experimental Approach to the Problem

A repeated-measures, crossover, experimental design was used. The practical experiment was conducted after the end of the competitive season 2013/2014, in which participants played a total of 37 games (30 official and 7 preseason games) and trained for over 330 hours (250 hours of basketball practice and 80 hours on strength sessions). Procedures lasted 3 weeks, with participants being tested once every week. In week-0, on the same day, all participants were tested in resting conditions (REST) and completed a familiarization set of the resistance training protocols. They were then randomly divided in 2 groups (G1 $n = 4$, G2 $n = 5$) so that it was possible to properly monitor the strength training and testing procedures. On week-1 and week-2, subjects performed two different resistance training protocols–High-Resistance Circuit Training (HRC) (2) and Power Circuit Training (PCT)–always followed by the same testing procedures performed on week-0. G1 executed the HRC on week-1 and PCT on week-2. G2 completed the PCT on week-1 and HRC on week-2. For each group, resistance training and testing were performed on the same day of the week at the same hour of the day.

Subjects

Nine semiprofessional male basketball players (Table 1) competing in the Spanish League EBA (fourth division), with at least 5 years of playing experience and 1 year involvement in resistance training, volunteered to participate in this study. None of them had a previous history of injuries, diseases, or was on medications during the study. Players were fully informed about all testing and training procedures and signed written informed consent. Before the study, all of them underwent a physical examination by the team physician and were cleared of any endocrine disorder that might confound or limit their ability. Approval for the study was given by the Human Subjects Ethics Committee of the San Antonio Catholic University of Murcia, Spain, in accordance with the Declaration of Helsinki (2008). Participants were instructed to maintain their normal diet habits and the team's regular practice schedule of 4 basketball-training sessions per week throughout the investigation period.

Testing Procedures

All testing measurements were completed in the UCAM Research Center for High Performance Sports (Murcia, Spain) at the end of the competitive season. Procedures were performed after 36 hours of rest, during the recovery microcycle, to limit differences in the training status and/or intensity (30). Participants were tested in 3 separate

TABLE 1. General characteristics of the participants ($n = 9$).*

Age (y)	Height (cm)	Body mass (kg)	BMI (kg/m^2)	Half squat 1RM (kg)	Bench press 1RM (kg)
21.44 ± 2.5	197.69 ± 8.38	93.19 ± 14.46	23.77 ± 12.93	157.44 ± 21.98	85.82 ± 20.26

*BMI = body mass index; 1RM = 1 repetition maximum.

occasions: (a) on REST, the week before the beginning of the training protocols; (b) immediately after the HRC training session, and (c) immediately after the PCT training session. On week-0, the first day of testing, participants completed a standard warm up of 5 minutes light jogging on the treadmill followed by the joint mobility exercises and dynamic stretching routine; the team executed in their regular basketball practices. No static stretching was performed before testing (42). On this day, after all tests were concluded, the 6RM load for all exercises was determined. An initial resistance was selected based on the subject's perceived capacity to move the load only 6 times. After the first set, if ±1 repetition was completed, the load was adjusted by approximately 2%, and if subjects were able to lift ±2 repetitionsit was accommodated by 5%.

The testing sequence lasted 34 minutes for each player and consisted of a 3-point shooting test, horizontal and vertical jump tests, an agility test, an RSA test, and a bench-press power output test. Players were familiar with all the testing procedures as they had performed them during the season. The order of the tests was kept the same in all 3 sessions and each assessment was conducted by the same investigator in every occasion. The same certified strength and conditioning coach (NSCA-CSCS) supervised all the testing and training procedures.

Three-Point Shooting Test. The shooting test performed was the 1 described by Pojskić et al. (28) for 3-point shooting without fatigue. Each player performed 2 jump shots from behind the 3-point line and from 5 different positions, with a total of 10 shots per series. The positions were determined with marks on the floor so that the players shot from the exact same place on every series. A total of three series were completed, but only the last two were considered for analysis, because the first was a warm up. Each testing series was separated by 2 minutes. The selected test has been considered as a valid and reliable instrument to measure basketball 3-point shooting accuracy (28) and was performed 3 minutes after the end of the resistance training protocols.

Horizontal Jump Test–Standing Long-Jump. The standing long-jump (SLJ) was performed with participants starting before a line drawn on the floor, feet pointing forward and placed at shoulder width, and then jumping as far as possible, landing on two feet. Arm-swing and a countermovement were allowed (23). Participants performed two practice trials and then two test trials separated by 1 minute of rest. The distance, measured to the nearest 0.01 m, was considered as the horizontal displacement of the feet between the starting line and the point where the back heel contacted the floor. Only the best result was considered for analysis. The test was performed 8 minutes after resistance training.

Vertical Jump Test–Countermovement Jump. The countermovement jump (CMJ) was performed on a Kistler 9286BA portable force platform (Kistler Group, Winterthur, Switzerland). Players started in a standing position with feet placed at shoulder width, on the center of the force platform, and were asked to jump as high as possible with a rapid countermovement. Hands were kept on the hips throughout the execution of the jump. The depth of the countermovement was self selected and subjects were asked to try and land close to the point of takeoff (23). Participants executed 2 submaximal trials to ensure proper execution of the jump and performed 2 maximal CMJ on the force platform with 1 minute of rest between them. Only the best attempt was considered. The parameters calculated were: (a) jump height, based on the velocity at takeoff and (b) absolute peak power and relative peak power, calculated with Microsoft Excel software (Microsoft Corporation, Redmond, WA, USA) from the data exported from the force platform. The CMJ has been considered the most reliable and valid test for the estimation of explosive power of the lower limbs (23). It was executed 10 minutes after the end of strength training.

Agility Test–Agility T-Test. The agility T-Test was performed using the standard protocol (37). At the tester's signal, players sprinted 9.14 m forward to the first cone and touched it. Then, subjects shuffled 4.57 m to the left and touched the second cone. After that, they shuffled 9.14 m to the right and touched a third cone and then 4.57 m to the left, back to point where the first cone was, touching it again. Finally, participants backpedaled 9.14 m, passing through the finish line. Time was measured with wireless photocells from Microgate's WITTY System (Mircrogate, Bolzano, Italy) placed on the starting line. Time started counting once the players broke the light beam the first time and stopped when they broke it the second time. Participants were verbally encouraged throughout the test and were asked to perform at the maximal effort. The only parameter considered was the total time. Two trials were allowed for each testing session, separated by 2 minutes. Only the best time was considered. Agility T-Test is a reliable and valid instrument (37) and was performed 17 minutes after the end of the resistance circuit protocols.

Repeated-Sprint Ability Test. The RSA protocol used was the one proposed by Castagna et al. (6) and consisted of 10 shuttle-run sprints of 30 m (15 + 15m) with 30 seconds rest between each bout. An excellent reliability and validity of this basketball-specific test has been reported (6). Wireless photocells from Microgate's WITTY System (Mircrogate) were placed in the starting line to record the time of each sprint. Participants were asked to perform at the maximal effort and verbal encouragement was given throughout the test. The parameters calculated were: (a) total time, consisting of the sum of all 10 sprint times; (b) ideal time, calculated as the best sprint time multiplied by 10; and (c) performance decrement (PDec; %), determined according to the equation proposed by Fitzsimons et al. (13):

$$P_{Dec} = 100 \times (\text{total sprint time}/\text{ideal sprint time}) - 100.$$

The RSA test was performed 23 minutes after the end of the strength training.

Bench-Press Power Output Test. The bench-press power output test was conducted on a modified Smith machine with a linear encoder (Chronojump-BoscoSystem, Spain) attached to the barbell and interfaced with a computer. All data were recorded with Chronojump-BoscoSystem software. The test was completed with each participant's bench-press 6RM load that was previously determined. Participants completed 3 repetitions descending the barbell to the point at which it nearly touched the chest and were verbally encouraged throughout the exercise to move the barbell as fast as possible in the concentric phase. Peak power was measured and only the best repetition was considered. A spotter was used during the test to assist in racking the resistance and to ensure safety and proper range of motion. This test was performed 33 minutes after resistance circuit training was completed each time.

Rating of Perceived Exertion–Borg CR-10 Scale. Rating of perceived exertion (RPE) was assessed on week-1 and week-2 using the Borg CR-10 scale (4). Participants were instructed on how to use the scale before the start of resistance training, on week-1. They were shown the RPE table to clearly understand what each number represented. Approximately 20 minutes after both HRC and PCT and before performing the RSA test, participants were asked "*How was your workout?*" and presented with the table. This time frame was selected so that the difficult or easy elements that were performed close to the end of the session would not tilt the RPE of the entire bout (8).

Training Protocols

The HRC protocol was based on the one proposed by Alcaraz, et al. (2). It consisted of 6 exercises, divided in 2 blocks of 3 (Figure 1). Participants completed 4 sets of each block with the previously determined 6RM load for every exercise. The local recovery, for each muscle, was 3 minutes (time separating 1 set of a given exercise to the next set of same exercise) and 40 seconds was the rest period between exercises. The training session started with a warm up consisting of 5 minutes of light jogging on the treadmill followed by joint mobility exercises and dynamic stretching. The specific warm up consisted of 1 set of 10 repetitions of each exercise of the first block with 50% of the 6RM load. The second block started 5 minutes after the end of block 1. The first 3 minutes between the two blocks consisted on a passive rest period and the final 2 minutes were destined to the specific warm up of the second block. Upper- and lower-body muscle groups were alternated in consecutive exercises to allow for local recovery to occur. Rest intervals shorter than 3 minutes for the same exercise do not allow participants to maintain the number of repetitions at the same intensity (33).

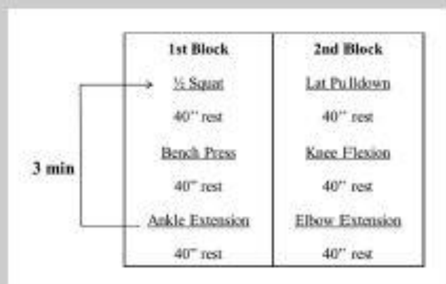

Figure 1. Resistance training protocol for both high-resistance circuit training (HRC) and Power Circuit Training (PCT). The exercises performed, exercise order, rest period between exercises, and local recovery time were all kept the same in both training conditions. The sole difference between HRC and PCT regarded the training intensity and working loads.

Players were verbally encouraged to execute the concentric phase of all exercises at the maximum possible velocity and lifted weights that allowed only 6 repetitions to be performed. If necessary, during the workout, the 6RM loads were adjusted for every set by 2%, if a participant performed ±1 repetition, or by 5%, if he completed ±2 repetitions.

The PCT protocol was very similar to the HRC. The training consisted of the same 6 exercises divided in the same 2 blocks (Figure 1). The warm up protocol was identical, as were the duration of the rest periods between exercises, the local recovery, and the number of sets and repetitions performed. The main differences between the PCT and HRC protocols were on the loads lifted, on the velocity of execution of the exercises, and whether these were performed to volitional fatigue or not. The PCT protocol was executed with the loads corresponding to maximal power output in basketball players, 45% of 1RM (32), and volitional fatigue was not achieved. The 1RM load was estimated using the Brzycki equation; previously considered a valid method (27).

Given that the loads were considerably lower, the velocity on the execution of the exercises was higher than in HRC. Participants were verbally encouraged to execute the concentric phase at the maximum possible velocity. For safety reasons, they were not allowed to jump on the half squat or to lose contact with the barbell on the bench press.

In both training protocols the concentric–eccencentric ratio was the same, 1:3. Spotters were present in every station of the circuit to ensure safety to the participants and to control the rest periods. The duration of HRC and PCT sessions was 45 minutes.

Statistical Analyses

Statistical analysis was conducted using IBM SPSS Statistics 21 for Windows (IBM Corporation, Armonk, NY, USA). All the data were expressed as mean ± SD. Normality was assessed with the Shapiro–Wilk test and homogeneity of

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variances with the Levene test. Parametric tests were applied. Repeated-measures analysis of variance, with intervention (training protocol) as factor, was performed to examine within-subject differences among REST, HRC, and PCT. Bonferroni adjustment of the confidence interval for multiple comparisons was used to locate the pair-wise differences between the mean values. Power ($1-\beta$) was determined for all variables and effect sizes (d) were calculated using Cohen's d. Statistical significance was considered for $p \le 0.05$.

Results

Vertical and Horizontal Jumps

The CMJ height ($1-\beta = 0.87$; $d = 0.61$), absolute ($1-\beta = 0.96$; $d = 0.73$) and relative peak power ($1-\beta = 0.95$; $d = 0.72$) values, and SLJ horizontal distance ($1-\beta = 1.00$; $d = 0.89$) were determined in all testing conditions (Table 2). The HRC protocol provoked a significant decrement ($p \le 0.05$) in all variables studied. These declines were significantly lower ($p \le 0.05$) when compared to PCT. No statistical significance was found between PCT and REST values.

Shooting

On the 3-Points shooting test, the parameters calculated were the total number of shots made ($1-\beta = 0.99$; $d = 0.74$), number of shots made per series ($1-\beta = 0.989$; $d = 0.74$), and shooting percentage ($1-\beta = 0.99$; $d = 0.74$) (Table 2). After the completion of the HRC training the shooting accuracy was significantly lower ($p \le 0.05$), compared to the other 2 testing conditions. No statistical significance was found between PCT and REST values.

Repeated-Sprint Ability and Agility

Values obtained in RSA test and agility T-Test are expressed in Table 2. The RSA total time ($1-\beta = 0.99$; $d = 0.81$) was higher ($p \le 0.05$) after the HRC session, when compared to the PCT session and REST. Concerning the RSA ideal time ($1-\beta = 1.00$; $d = 0.85$), the trend was similar. The slowest performance was found after the HRC training, followed by PCT and REST. There were significant differences ($p \le 0.05$) between HRC and REST and between HRC and PCT, but not between REST and PCT. Regarding RSA PDec ($1-\beta = 0.77$; $d = 0.54$), values were lower on REST than after either resistance training protocols. The only significant differences ($p \le 0.05$) were found between HRC and REST.

In the agility T-Test, results showed that after HRC training, the total time ($1-\beta = 1.00$; $d = 0.86$) was significantly higher ($p \le 0.05$) than in the other 2 conditions, indicating a lower performance. No statistical differences were found between PCT and REST.

Table 2. Performance measurements for all variables on the three experimental conditions.*

	REST	HRC	PCT
CMJ			
Height (m)	0.35 ± 0.07	0.28 ± 0.08†	0.33 ± 0.07‡
Absolute peak power (W)	5078.18 ± 436.83	4400.74 ± 430.01†	4819.44 ± 341.55‡
Relative peak power (W/kg)	55.70 ± 6.52	48.43 ± 7.39†	52.66 ± 7.06‡
SLJ			
Distance (m)	2.47 ± 0.25	2.36 ± 0.25†	2.43 ± 0.26‡
3-points Shooting			
Total shots made	9.67 ± 1.70	7.78 ± 1.40†	10.56 ± 2.59‡
Total shots made per series	4.83 ± 0.85	3.89 ± 0.70†	5.28 ± 1.29‡
Total shooting percentage (%)	48.33 ± 8.50	38.89 ± 6.98†	52.78 ± 12.93‡
Repeated-Sprint Ability			
Total time (s)	57.50 ± 2.89	59.24 ± 3.32†	58.08 ± 3.33‡
Ideal time (s)	55.88 ± 2.68	56.90 ± 2.82†	56.23 ± 3.02‡
Performance decrement (%)§	2.89 ± 0.96	4.22 ± 0.75†	3.29 ± 0.94
Agility T-Test			
Total time (s)	9.52 ± 0.63	9.71 ± 0.69†	9.54 ± 0.72‡
Bench press			
Power output (W)	595.40 ± 80.25	518.58 ± 95.32†	574.94 ± 93.57‡
Borg CR-10 Scale			
Rating of perceived exertion (UA)‖		7.89 ± 0.57	4.33 ± 0.94‡

*REST = resting conditions; HRC = high-resistance circuit training; PCT = power circuit training; CMJ = Countermovement jump; SLJ = standing long-jump.
†$p \le 0.05$, as related to resting conditions.
‡$p \le 0.05$ as related to HRC.
§Performance decrement (PDec) was calculated with the following equation (13): PDec = 100 × (total sprint time/ideal sprint time) − 100.
‖Rating of perceived exertion was assessed with a Borg CR-10 Scale, 20 minutes after training (8).

Bench-Press Power Output

The bench-press power output ($1-\beta = 0.88$; $d = 0.62$) values obtained (Table 2) indicated that performance was significantly lower ($p \leq 0.05$) in HRC when compared to both REST and PCT. No statistically significant differences were found between PCT and REST.

Rating of Perceived Exertion–Borg CR-10 Scale

The RPE ($1-\beta = 1.00$; $d = 0.90$) (Table 2) was assessed with the Borg CR-10 Scale and results showed that participants considered the HRC training as being more intense than the PCT protocol. According to the Borg CR-10 Scale, HRC was perceived as "*Very Hard*" and PCT as "*Somewhat Hard*." The differences were statistically significant with $p \leq 0.05$.

Discussion

To the best of our knowledge, this is the first study that has investigated the acute effects of HRC and PCT on basketball-specific physical and technical skill performance. The main findings supported our hypothesis because immediately after a PCT bout, CMJ and SLJ performance, shooting accuracy, RSA, agility, and upper body power output were not negatively affected in basketball players. Furthermore, performing a PCT session was perceived as less intense than completing an HRC bout. These findings suggested that power training may be the most appropriate option before a practice or game, as it avoids acute resistance training-induced performance decrements and minimizes fatigue, thus preventing an increased risk of injury (10). However, if the objective of the basketball session is to develop or perfect technical skills under fatiguing conditions, hence HRC may be the more suitable option.

Previous studies have also demonstrated increased levels of fatigue after high-intensity resistance training (17,20). Linnamo et al. (20) showed that maximal strength training led to greater neuromuscular fatigue than power training using 40% 1RM. This is in accordance with the performance decrements observed in all variables measured in our basketball players, after HRC compared to PCT.

Shooting, which is the most important action in basketball, can be affected by fatigue (28,39). Its accuracy depends on an adequate technique (39) and our results showed that after HRC, the total number of shots made, mean shots made per series, and total shooting percentage were significantly lower. The present data support the idea that the magnitude of immediate fatigue and its recovery are dependent on the intensity of the performed task (29). In fact, higher levels of fatigue have been shown to affect motor skill outcomes in basketball players (19,21,28). This may not be necessarily a negative aspect if the objective of the practice is to perform shooting drills when players are already fatigued, as it occurs in competition. In reality, some teams combine high-intensity strength training with low-intensity technical sessions (22) due to time limitations during the competitive season (35). Although basketball shooting kinematics was not analyzed in our study, modifications in the movement pattern most probably occurred because of fatigue. This phenomenon has been reported in previous research with elite basketball players (39). Another interesting finding is that our data seems to be the first to indicate that basketball-specific motor skills remain unaltered in trained individuals immediately after a moderate-intensity strength training session. Kauranen et al. (18) had already reported that the motor skill performance of the hand (reaction time, speed of movement, tapping speed, and coordination) was not altered immediately after moderate-intensity training. However, those results were obtained with untrained subjects.

Other important factors related to success in basketball are the jumping ability and power output production. Thus, CMJ and SLJ are commonly used to assess the basketball players' physical fitness (43). Our data indicated a decline in jump performance after HRC, and moreover, several studies have shown that fatigue negatively affects vertical jump performance (31,36). It is probable that the main mechanisms responsible for the diminished CMJ and SLJ performance were peripheral in the origin, given the time elapsed between the end of resistance training and both tests was 10 minutes (29). Raastad and Hallen (29) suggest that 5 minutes after exercise cessation, the reduced neural activation is practically recovered and, so, central fatigue was not a major factor of decrements in CMJ height. Furthermore, declines in the power output of dynamic tasks have been associated to peripheral fatigue, specifically to a reduction of shortening velocity (17). This phenomenon can be related to other variables of our study's as the same mechanisms were responsible for the declines observed in bench-press power output after HRC. Although there are differences in fatigability of upper and lower body, declines in power and velocity are believed to be peripheral in the origin of both CMJ and bench press (34).

In basketball players, a significant correlation between the CMJ and RSA has been reported (38). As previously observed in our study, a decline in CMJ performance occurred after HRC. Hence, RSA could be expected to be affected as well. In effect, concerning this latter variable, the performance declined after HRC. Participants were significantly slower completing the whole 10 sprints and also fatigued more throughout the protocol. Although no studies have investigated the effects of resistance training on RSA performance, the decrements observed may be related to the fact that an HRC session was performed. Heavy-resistance training leads to a high rate of energy utilization through phosphogen breakdown and activation of glycogenolysis, which results in significant decreases in ATP and muscle glycogen concentration (40). In fact, preceding high-intensity efforts may compromise RSA due to limitations in energy supply, mainly from phosphocreatine, and alterations in muscle excitability related with sodium or potassium disturbances at the muscular level (15).

The main energy metabolisms involved in RSA are most likely the same as in the agility T-Test since this latter test consisted of maximal effort completion, in all three experimental conditions, in less than 10 seconds. Analyzing the results, we observed increases in total time only after HRC. We consider the causes for performance declines in agility were the same as in the RSA effort. Possible decreased muscle glycogen concentration (19,40) and postresistance-training impaired muscle contractile function (17) contributed to the results obtained. Meylan et al. (25) state that sudden bursts of power are needed to rapidly change direction during athletic actions, and as our CMJ results showed, lower-body power production was impaired, which possibly contributed to reduce participants' agility.

As stated before, our results indicated that fatigue was greater after HRC when compared to PCT. This conclusion was also sustained by the subjects' perception of effort in following each protocol. The RPE was significantly higher after HRC, which is not surprising because of the relationship between the RPE and resistance training intensity (8). Day et al. (8) conducted a study in which participants completed, on separate days, the same resistance training protocol with different loads (5RM, 10RM, and 15RM) and concluded that lifting heavier loads was perceived as more difficult. Heavy-resistance training requires greater muscle tension development that results in an increment of motor unit recruitment and firing frequency, thus increasing the perception of effort (8).

The main methodological limitation of this study was the small sample size, although medium- to large-effect sizes were obtained for all variables. Another limitation was the fact that the last assessment was completed more than 30 minutes after the end of both resistance protocols because all tests were performed in sequence, in the same session. The long recovery period between some tests and the end of the training could have influenced the results. However, the order of the testing was the same for each participant in all the sessions.

Further studies are needed to determine the fatigue mechanisms that lowered performance as the methodology used did not allow for the determination of such mechanisms. Furthermore, the long-term effects of these two resistance training protocols on the variables studied are still unknown for basketball players.

Practical Applications

The results of this study may be useful for strength and conditioning coaches to plan their sessions more effectively. Our data show that a PCT session may be an appropriate option for basketball players to complete before a tactical session or game, as it avoids acute resistance training-induced performance decrements. Jumping performance, shooting accuracy, RSA, agility, and upper body power output are not negatively affected. In contrast, postsession performance impairments in the main determinants of success in basketball are present after an HRC session, for at least 30 minutes. This may lead to a decline in the quality of the practice or game and to an increased risk of injury.

Nonetheless, HRC is important to develop or maintain maximal strength. For this reason it should be included in the strength program of a basketball team. Sessions of HRC may be a suitable alternative when the objective of the oncourt practice is to develop or perfect technical skills under fatiguing conditions, as it occurs in competition.

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APPENDIX 2. Study 2: SHORT-TERM ADAPTATIONS FOLLOWING COMPLEX TRAINING IN TEAM-SPORTS: A META-ANALYSIS

Reference:

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RESEARCH ARTICLE

Short-term adaptations following Complex Training in team-sports: A meta-analysis

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Abstract

Objective

The purpose of this meta-analysis was to study the short-term adaptations on sprint and vertical jump (VJ) performance following Complex Training (CT) in team-sports. CT is a resistance training method aimed at developing both strength and power, which has a direct effect on sprint and VJ. It consists on alternating heavy resistance training exercises with plyometric/power ones, set for set, on the same workout.

Methods

A search of electronic databases up to July 2016 (PubMed-MEDLINE, SPORTDiscus, Web of Knowledge) was conducted. Inclusion criteria: 1) at least one CT intervention group; 2) training protocols ≥4-wks; 3) sample of team-sport players; 4) sprint or VJ as an outcome variable. Effect sizes (ES) of each intervention were calculated and subgroup analyses were performed.

Results

A total of 9 studies (13 CT groups) met the inclusion criteria. Medium effect sizes (ES) (ES = 0.73) were obtained for pre-post improvements in sprint, and small (ES = 0.41) in VJ, following CT. Experimental-groups presented better post-intervention sprint (ES = 1.01) and VJ (ES = 0.63) performance than control-groups.

Sprint

large ESs were exhibited in younger athletes (<20 years old; ES = 1.13); longer CT interventions (≥6 weeks; ES = 0.95); conditioning activities with intensities ≤85% 1RM (ES = 0.96) and protocols with frequencies of <3 sessions/week (ES = 0.84). Medium ESs were obtained in Division I players (ES = 0.76); training programs >12 total sessions (ES = 0.74).

VJ

Large ESs in programs with >12 total sessions (ES = 0.81). Medium ESs obtained for under-Division I individuals (ES = 0.56); protocols with intracomplex rest intervals ≥2 min (ES = 0.55); conditioning activities with intensities ≤85% 1RM (ES = 0.64); basketball/volleyball players (ES = 0.55). Small ESs were found for younger athletes (ES = 0.42); interventions ≥6 weeks (ES = 0.45).

Conclusions

CT interventions have positive medium effects on sprint performance and small effects on VJ in team-sport athletes. This training method is a suitable option to include in the season planning.

Introduction

In team-sports, the capacity to maximize neuromuscular power production is fundamental to success and critical to achieve high levels of performance and greater velocities in sport specific movements [1]. The improvement of high intensity, explosive actions such as sprint or vertical jump (VJ) is an important goal for coaches and athletes [2, 3]. In fact, Faude et al. [4] concluded that straight sprints are the most important action when scoring or assisting a goal in elite football. For the purpose of this meta-analysis, it is important to state that in most team-sports the distances covered in sprint efforts are usually short [5–7] and consist primarily on accelerations and decelerations without developing full speed [8].

Studies conducted with American Football athletes have shown that Division I players are stronger, faster and more powerful than their Division II or Division III counterparts [9]. Also, Cometti et al. [10] reported that elite soccer players displayed higher strength values and 10 m sprint performance when compared to amateurs. This indicates that strength and power production may differentiate athletes from different competition levels. Therefore, due to the association between these variables and higher performance levels in team-sports, investigating about training methods designed to improve strength and neuromuscular power is of great interest.

Research has shown that resistance training performed with heavy loads as well as programs using light or optimal loads, plyometric training and ballistic exercises lead to increments in maximal power outputs [1], VJ [3, 11–13] and sprint performance [2, 3, 13, 14]. Traditional heavy resistance strength training results in increments in maximal strength and power by targeting mainly the force component of the power equation (power = force x velocity) [1, 15]. However, this type of loading does not play a relevant role in maximal power improvements after reasonable levels of strength are attained [1, 15]. On the contrary, plyometric and ballistic/power exercises performed with lighter loads allow for higher movement velocities to be achieved, which elicits specific adaptations in neural drive that ultimately lead to an increased rate of force development and maximal power production [1, 13, 15]. Finally, methods that combine both strength and power exercises may produce superior improvements in sprint and VJ when compared to strength, power or speed training alone in untrained subjects [12, 16] and athletes [17].

Most recently, Complex Training (CT) has emerged as a training method aimed at developing strength and neuromuscular power. It consists on coupling biomechanically similar heavy load resistance exercises (also referred to as conditioning activities (CA)) with plyometric or power exercises (maximal movement velocities), set for set, in the same workout [18, 19]. Two consecutive exercises combined are termed a complex pair [20] (a back squat followed by a countermovement jump, for example). According to Ebben [19], heavy resistance training increases motoneuron excitability and reflex potentiation, thus possibly creating optimal training conditions for subsequent neuromuscular power gains. Furthermore, Cormie et al. [1] state that the ability to generate maximal power depends greatly on the ability of the nervous system to activate the muscles involved with the adequate order and magnitude of activation.

Theoretically, CT improves performance due to the enhancement of the muscle's explosive capability after being subjected to maximal or near maximal contractions, in a response known as postactivation potentiation (PAP) [20–22]. The phosphorylation of myosin regulatory light chain [21] and the recruitment of higher order motor units that occurs after maximal muscle contractile activity [21, 23] are the mechanisms believed to contribute to PAP. Seitz and Haff [22] performed a meta-analysis on the factors modulating PAP of jump, sprint, throw and upper-body ballistic performances. According to the authors, performing a CA produces small PAP on jump and moderate on sprint. Furthermore, PAP effects seem to be higher in stronger individuals (squat:body mass ratio $\geq$1.75 for men and >1.5 for women) and when the CA consists on plyometric drills or resistance exercises $\geq$85% of 1RM. The results also indicated that the greatest PAP response is obtained after longer recovery intervals ($\geq$5 min) between the CA and the subsequent exercise and also when multiple sets are performed instead of a single one [22]. However, it has also been suggested that CA may have a warm-up effect rather than an actual potentiating one [24] and that this should not be excluded as a possible cause for the improved performance in the subsequent exercise.

CT is considered a time efficient method [25], but there is no clear agreement on its actual effectiveness [26]. Several studies [27–29] investigated its acute effects, mainly focusing on identifying if PAP was present after the CA and if performance increased. Results found were somehow contradicting, since some investigations [29, 30] indicated that CT resulted in subsequent acute increments in power production whereas other studies reported no significantly higher performance gains [27, 28]. Factors like training background [26, 29], subjects' strength level [20, 29, 31], intracomplex rest interval [22, 26, 31] or the load used in the CA [22, 30, 31] have been proposed as influential in the acute response to CT.

Concerning short- and long-term adaptations, few studies have been conducted to assess the efficacy of CT protocols. Research on recreationally trained individuals indicated that CT did not result in higher whole- and lower-body power output increments when compared to compound training (strength and power sessions on alternate days) [32] or when compared to resistance training only or plyometric training alone [25]. Furthermore, maximal strength adaptations were similar in all different training conditions [25, 32]. Regarding team-sports athletes, disparities can be found within the results published in the literature. Faude et al. [33] found increases in lower body maximal strength and VJ height following a CT intervention with soccer players, but no improvements in 10 and 30 m sprint or agility. McMaster et al. [34] reported increases in both maximal strength and sprint ability in rugby players following CT and Alves et al. [35] obtained significant improvements in sprint (5 and 15 m) but not in countermovement jump or agility performance in soccer players. Other studies reported increases in sprint [36, 37] or VJ [38–40] performance or no positive adaptations on these variables after a several weeks CT program [41].

It remains controversial as to whether CT has a positive effect on sprint or VJ in team-sports but a recent meta-analytical review on the effects of resistance training in youth athletes concluded that for muscular power development, CT provided a greater magnitude of change compared with other resistance training protocols [42]. This suggests that CT may be a promising method to develop neuromuscular power and athletic performance but further understanding on how to organize its training variables is necessary.

Therefore, the main aim of this meta-analysis was to examine the effects of short-term CT interventions (at least 4 weeks) on sprint and VJ performance in team-sport athletes and to identify the possible moderating factors contributing to such adaptations.

Methods

Literature research and data sources

This research was completed in accordance with the recommendations of the PRISMA statement (S1 Table) [43]. The literature research was conducted in different online databases: PubMed MEDLINE, SPORTDiscus and Web of Knowledge (WoS). The search included studies published until July 2016 and the following keywords were introduced, either individually or combined: "complex training", "postactivation potentiation", "performance", "athletes", "players", "sprint" and "jump". Reference lists from relevant articles were also scrutinized to find other potentially eligible studies.

Inclusion and exclusion criteria

Crossover, randomized, non-randomized and counterbalanced studies published in English were considered for inclusion and no age or sex restrictions were imposed. Studies were included if the following criteria was met: 1) at least one of the study's group was submitted to a CT intervention containing lower-body exercises, in which CT consisted of biomechanically similar (same movement pattern) heavy load resistance training exercises combined with plyometric/explosive exercises, set for set, in the same workout [18, 19]. Studies that combined strength training and plyometric in a different manner (e.g. all strength exercises in the first part of the workout and all plyometric in the end of the session) were not considered; 2) interventions were of at least 4-weeks; 3) participants were athletes currently engaged in team-sport activities, and presented no cardiovascular, metabolic, or musculoskeletal disorders and no history of doping or drug abuse; 4) sprint or VJ were outcome variables measured.

With respect to the exclusion criteria, studies were not considered if: 1) the article was not published in English; 2) no full-text was available; 3) no CT intervention group was present; 4) only acute effects were investigated; 5) participants were not team-sport athletes; 6) sprint or VJ were not outcome variables;

Study selection

The initial search was conducted by one researcher (TTF). After the removal of duplicates, titles and abstracts were screened and studies not related to the review's topic were excluded. Following the first screening process, the full version of the remaining articles was read. Then, on a blind, independent fashion, two reviewers selected the studies for inclusion (TTF and AMR), according to the criteria previously established. If no agreement was obtained, a third party intervened and settled the dispute.

Data extraction and analysis

Mean, standard deviation (SD) and sample size data were extracted by one author (TTF) from tables of all included papers. Whenever necessary, contact was made with the authors to get the data. Any disagreement was resolved by consensus (TTF, AMR), or third-party adjudication (PEA). The meta-analysis and statistical analyses were performed using Review Manager software (RevMan 5.2; Cochrane Collaboration, Oxford, UK) and Comprehensive Meta-analysis software (Version 2; Biostat, Englewood, NJ, USA). For each study, mean differences and 95% confidence intervals (CI) were calculated with Hedges' g [44] for continuous outcomes.

Each mean difference was weighted according to the inverse variance method [45]. Since sprint time and VJ height were assessed by different methods, the mean differences were standardized by dividing the values with their corresponding SD. The standardized mean difference (SMD) in each trial was pooled with a random effects model [46]. The ESs were calculated using Cohen's d with the following equation [47], for paired samples:

$$ES = \frac{M_{pre} - M_{post}}{SD_{pre}}\left(1 - \frac{3}{4n - 5}\right)$$

where M_{pre} is the mean value before the CT intervention, M_{post} is the mean after the intervention, n is the sample size of CT group and Spre is the SD pre-intervention. Additionally, for independent samples (training and control groups (CG)), the ESs were calculated with the formula [47]:

$$ES = \frac{M_1 - M_2}{SD_{pooled}}$$

where M_1 is the mean value of the intervention group post CT intervention, M_2 is the mean of the CG after the intervention and the SD_{pooled} is calculated:

$$SD_{pooled} = \sqrt{\frac{SD_1{}^2 + SD_2{}^2}{SD_{pooled}}}$$

ESs were considered small (ES = 0.2), medium (ES = 0.50) and large (ES = 0.80) [47]. The data analysis was focused on the magnitude of effects obtained.

Heterogeneity among studies was assessed using I^2 statistics. I values range between 0% and 100% and are considered low, modest or high for <25%, 25±50%, and >50%, respectively. Heterogeneity may be assumed when the p-value of the I test is <0.05 and may be due to the variability between the characteristics of the participants of the studies included (age, sex, etc) [48].

Potential moderating factors were evaluated by subgroup analysis comparing trials grouped by dichotomous or continuous variables potentially influencing sprint time and VJ height. Median values of continuous variables were used as cut-off values for grouping trials. Changes in potential moderating factors were expressed and analysed as post minus pre-intervention values. Publication bias was evaluated by estimating funnel plot asymmetry test. Statistical significance was considered for $p \leq 0.05$.

Risk of Bias

Methodological quality and risk of bias were assessed by visual interpretation of the funnel plot, by two authors independently (TTF, AMR), with disagreements being resolved by third part evaluation (PEA), in accordance with the Cochrane Collaboration Guidelines [45].

Results

Characteristics of included studies

A total of 1593 records were identified through database searches and 3 studies through reference lists. After abstract screening, from the 328 studies that were left following duplicates removal, 296 studies were excluded. As a result, 32 studies were assessed for eligibility. Of these, 23 were excluded for not meeting the inclusion criteria. Consequently, 9 studies [33–41] were included in this meta-analysis (Fig 1).

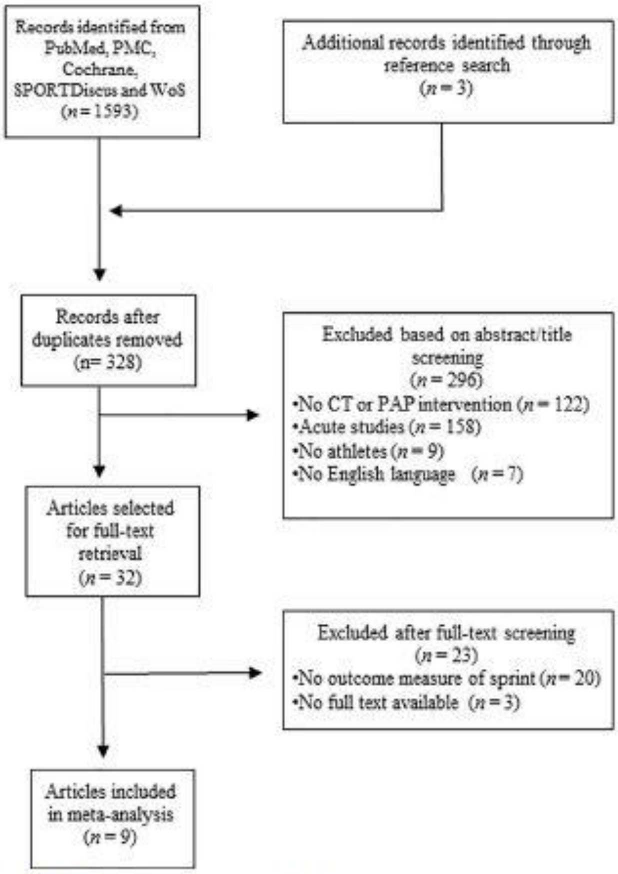

Fig 1. Flow diagram of the process of study selection.

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From the studies included, 4 [34, 35, 38, 41] presented two CT groups which accounted for a total of 9 subgroups analysed for the sprint variable and 8 for VJ. A CG was present in 5 of the studies [33, 35, 37, 40, 41].

The quality of the trials, according to a PEDro scale [49] was high. The mean score was 6.44 ± 1.01 out of a possible 10 points (Table 1).

Characteristics of the interventions

The different CT intervention groups' characteristics are present in Table 2. The intensity of the lower-body heavy resistance exercises performed ranged from 50% to 100% 1RM and the plyometric/power exercises from body mass to 75% 1RM (loaded CMJ). The interventions

Table 1. PEDro scale scores of the studies included in the meta-analysis.

PEDro Scale Items	Alves et al., 2010	Brito et al., 2014	Cavaco et al., 2014	Dodd et al., 2007	Faude et al., 2013	Kukric et al., 2012	McMaster et al., 2014	Mihalik et al., 2008	Watts et al., 2014
1. Eligibility criteria (item does not score)	1	1	1	1	1	1	1	1	1
2. Random allocation	1	1	1	1	1	1	1	-	1
3. Concealed allocation	1	1	1	1	1	1	1	-	1
4. Similar groups at baseline	1	1	1	1	1	-	1	-	1
5. Blinding of subjects	-	-	-	-	-	-	-	-	-
6. Blinding of therapists	-	-	-	-	-	-	-	-	-
7. Blinding of assessors	-	-	-	-	-	-	-	-	-
8. Measure of one key outcome– 85% of subjects	1	1	1	1	-	1	1	1	1
9. Intention to treat	1	1	1	1	1	1	1	1	1
10. Between-group comparison	1	1	1	1	1	1	1	1	1
11. Point estimates and variability	1	1	1	1	1	1	1	1	1
Total Score	7	7	7	7	6	6	7	4	7

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ranged from 4 to 10 weeks of duration with a frequency of 1 to 4 sessions/week. The distances covered in sprint assessment ranged from 15 to 30 m. Regarding VJ, three studies used a force platform to record jump performance [33, 38, 40], two utilized a Vertec device [36, 39] and one used a jump mat [35].

Main effects analysis

When all studies and respective CT groups were examined, results indicated medium training effects (ES = 0.73) on sprint performance ($p \leq 0.05$) and small (ES = 0.34) on VJ height ($p = 0.07$) following CT interventions (Figs 2 and 3). Furthermore, in the studies that presented a CG, experimental groups presented better post-intervention sprint time (ES = 1.01; $p = 0.05$) and VJ height (ES = 0.63; $p = 0.02$) than CG (Figs 4 and 5).

Subgroup analysis

Subgroup analysis assessing potential moderating factors for sprint time and VJ height are presented in Table 3. Regarding age, large ES were obtained for younger player (<20 years) in sprint (ES = 1.13) and small in VJ (ES = 0.42), independent of level of practice. For players over 20 years old, small ESs were found (sprint = 0.23; VJ = 0.20). With respect to the level of practice, an athlete was considered Division I (D1) if he was competing in first division of his respective sport, independent of the age category. All the players not competing in first division were considered under-Division I (U-D1). On sprint, both D1 (ES = 0.76) and U-D1 (ES = 0.70) athletes obtained medium training effects, independent of age On VJ, D1 athletes exhibited small ESs (0.2) and U-D1 medium (ES = 0.56).

Concerning training frequency, from all the studies that had VJ as an outcome variable, only one [35] had a frequency other than 2 times/week. Hence, subgroup analysis was only performed for sprint. Lower training frequencies induced a large training effect on sprint performance (ES = 0.84) whereas training 3 or more times/week exhibited small ESs (ES = 0.35).

Table 2. Characteristics of the studies included in the meta-analysis and complex training interventions, sprint time and vertical jump assessment.

	n						Complex Training Intervention					Sprint			Vertical Jump		
Study, year of publication	CG	CT	♀ (%)	Age	Sport	Level	Type	Freq (wk^{-1})	ICRI	Duration (wks)	Intensity CA	Measure	Units	Distance (m)	Measure	Units	Type
Alves et al. [35] 2010	6	9	0	17.4 ± 0.6	Soccer	D1	CT1:	1	No data	6	85% 1RM	Photoelectric cells	sec	15	Jump mat	cm	CMJ
							CTP1- Squat + High Skipping										
							CTP2- Calf Raises + VJ										
							CTP3- Leg ext + VJ from seated position										
		8	0				CT2:	2									
							Same as CT1										
Brito et al. [37] 2014	21	12	0	19.9 ± 0.5	Soccer	U-D1	CT:	2	20 sec	9	85% 1RM	Photoelectric cells	sec	20	N/A	N/A	N/A
							CTP1- Squat + High Skipping										
							CTP2- Calf Raises + VJ										
							CTP3- Leg ext + VJ from seated position										
Cavaco et al. [41] 2014	6	5	0	13.8 ± 0.45	Soccer	U-D1	CT1:	1	No data	6	85% 1RM	Photoelectric cells	sec	15	N/A	N/A	N/A
							CTP1- Squat + Sprint										
							CTP2 –Squat + Sprint with ball										
							CT2:	2									
							Same as CT1										
Dodd et al. [36] 2007	—	32	0	20.5 ± 2.5	Baseball	U-D1	CT: 3 HR combined with 3 PLY	2	<10 sec	4	85% 1RM	Hand-held stop watch	sec	18.3	Vertec device	Inch	Aba
Faude et al. [33] 2013	8	8	0	23.1 ± 2.7	Soccer	U-D1	CT: 2 day routine	2	<10 sec	7	90%/50–60% 1 RM	Photoelectric cells	sec	30	Force platform	cm	CMJ
							D1: Unilateral Half-Squat + Single Leg Jumps										
							D2: 2 of 4 CTP + 1 soccer-specific activity										
							CTP1- Half-Squat + DJ										
							CTP2- Calf Raises + High Straight Jumps										
							CTP3- Lateral Half-Squat + Lateral Jumps										
							CTP4- Step-ups + Bounding Jumps										
Kukric et al. [40] 2012	10	10	0	16.5 ± 0.5	Basketball	U-D1	CT:	2	5 min	10	80% RM	N/A	N/A	N/A	Force platform	cm	Aba
							CTP1- Standing on toes + Single leg jumps										
							CTP2- Leg Press + Jump over Hurdles										
							CTP3- Step forward + Telemark jumps										
							CTP4- Half-Squat + Jump over Hurdles										

(Continued)

Table 2. (*Continued*)

Study, year of publication	n: CG	n: CT	♀ (%)	Age	Sport	Level	Complex Training Intervention: Type	Freq (wk⁻¹)	ICRI	Duration (wks)	Intensity CA	Sprint: Measure	Sprint: Units	Sprint: Distance (m)	Vertical Jump: Measure	Vertical Jump: Units	Vertical Jump: Type
McMaster *et al.* [34], 2014	—	14	0	20.9 ± 1.6	Rugby	D1	**SHB**: 4 day routine	4	2 min	5	85-100/60-75% RM	Photoelectric cells	sec	20	N/A	N/A	N/A
							D1: CMJ + CM bench throws Power Cleans + Jammer Press DB Snatch										
							D2: CTP1- Bench Press + Bench Press Throws										
							CTP2- Chin-ups + High Pulls										
							CTP3- DB Floor Press + DB rows										
							D3: CTP1- Back Squat + Squat Jumps										
							CTP2- Bulgarian Split Squat + Speed Lunge										
							D4: CTP1- Incline DB press + Alternate DB bench press										
							CTP2- Hip Thrusts + Calf Raises										
							SLB: Same as SHB										
Mihalik *et al.* [38], 2008	—	15	67	20.3 ± 2.2	Volleyball	D1	**CT**: Squat + Depth Jump Single Leg Lunge + Split Squat Jump Deadlift + Double Leg Bounds	4	2 min	4	80% 1RM	N/A	N/A	N/A	Vertec device	cm	Abs
Watts *et al.* [38], 2014	—	4	0	16.8 ± 0.6	Volleyball	D1	**HRS**: 2 day routine	4	2 min	4	90% 3RM/ 90% 1RM	N/A	N/A	N/A	Force platform	cm	CMJ
							D1: CTP1- Power Snatch + Medicine Ball Throw										
							CTP2- Back Squat + Depth Jumps Front Squat										
							D2: CTP1- Power Clean + Spike Jump										
							CTP2- Front Squat + Standing Long Jumps Deadlift										
		5	0	17.9 ± 1.1			**LRS**: Same as HRS										

Data are mean, mean ± SD, n or range. C = control group; CT = complex training exercise-group; ICRI = Intracomplex Rest Interval; CA = Conditioning Activity; RM = Repetition Maximum; D1 = Division 1; U-D1 = Under Division 1; CTP = Complex Pair; HR = Heavy Resistance Exercises; PLY = Plyometric Exercises; CT1 = Complex Training group I; CT2 = Complex Training group 2; SHB = Strength Heavy Ballistic complex training group; SLB = Strength Light Ballistic complex training group; HRS = High Reactive Strength group; LRS = Low Reactive Strength group

https://doi.org/10.1371/journal.pone.0180223.t002

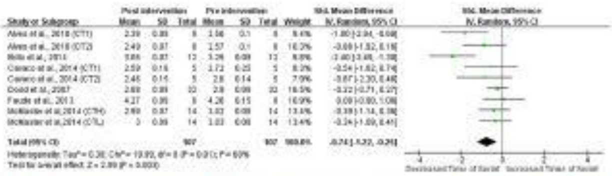

Fig 2. Standardized mean difference (SMD) between post and pre-intervention sprint time in CT-trained subjects. Squares represent the SMD[a] for each trial. Diamonds represent the pooled SMD across trials.

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Regarding the CA intensity, large ES (ES = 0.96) on sprint time was attained for intensities below 85% 1RM and small (ES = 0.25) for higher intensities (≥85%). As for VJ, results indicated a medium ES (ES = 0.64) with loads lighter than 85% 1RM. When the workout comprised loads heavier than 85% 1RM, negligible ES were found (ES = 0.15).

Regarding the duration of intervention, longer CT programs (≥6 weeks) presented large ESs for sprint (ES = 0.95) and small for VJ (ES = 0.45) while shorter training periods (<6 weeks) showed small ESs (sprint = 0.29 and VJ = 0.22).

Regarding the number of sessions, performing less than 12 resulted in a medium training effect (ES = 0.74) for sprint and a negligible for VJ (ES = 0.18). Completing more than 12 sessions displayed a medium effect (ES = 0.71) for sprint and a large for VJ (ES = 0.81).

With reference to intracomplex rest interval (ICRI), for sprint, 2 studies [35, 41] did not specify the rest between the CA and the subsequent exercise and from the remaining investigations [33, 34, 36, 37], just one presented a different rest interval [34]. Hence, no subgroup analysis was conducted for this variable. Regarding VJ, intervals longer than 2 min produced larger ESs (ES = 0.55) than shorter rest periods (ES = 0.15). However, 2 studies [35, 41] that did not report the time between the CA and the subsequent exercise were not considered in this subgroup analysis.

Finally, in relation to sport modality, athletes from team-sports in which jumping actions are more frequent and crucial for performance (basketball/volleyball) achieved medium training effects (ES = 0.55) after a CT intervention and players from other team-sports, negligible (ES = 0.12).

Evaluation of potential bias

At evaluation of potential bias, visual interpretation of the funnel plot for the SMD between pre and post intervention sprint time and VJ height in CT participants was considered notably symmetrical, suggesting the absence of a significant publication bias. Similar results were

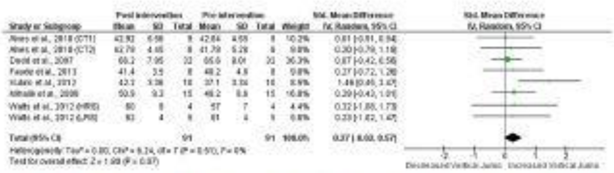

Fig 3. Standardized mean difference (SMD) between post and pre-intervention VJ height in CT-trained subjects. Squares represent the SMD[a] for each trial. Diamonds represent the pooled SMD across trials.

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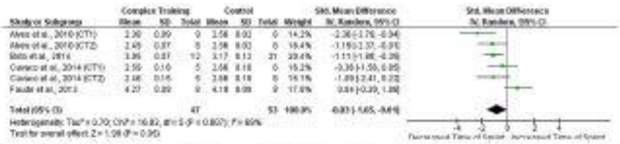

Fig 4. Standardized mean difference (SMD) in post-intervention sprint time between CT-trained and control subjects. Squares represent the SMD* for each trial. Diamonds represent the pooled SMD across trials.

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obtained for the evaluation of potential bias of the SMD in post-intervention sprint time and VJ height between CT and CG athletes.

Discussion

To the best of our knowledge, this is the first meta-analysis focusing on the short-term adaptations on sprint and VJ performance following CT in team-sports. The main findings indicated that this type of training lead to positive medium effects on sprint performance, over distances between 15 and 30 m. Regarding VJ height, small but positive effects were also found. Our results support the idea that CT, consisting on heavy resistance exercises coupled with plyometric/explosive exercises, set for set, on the same session, contributes to enhanced sprint and VJ performance [18–20]. The training variables that seem to most influence this positive response to CT in team-sports are the duration of intervention (≥6 weeks), the CA intensity (<85% 1RM) and the ICRI (≥2 min).

A second finding within the present meta-analysis is that, in the studies where a CG was present [33, 35, 37, 40, 41], intervention groups performed better than CG in both sprint and VJ. This is an interesting discovery given that players in CT and CG performed the same team practices, most probably containing short accelerations, sprinting, jumping and other high intensity actions characteristic of team-sports [6, 50, 51]. Therefore, we may assume that the increments found in sprint ability and VJ were due to the CT stimulus and not to the team practice [52].

An examination of the included studies shows discrepancies regarding sprint and VJ adaptations to CT. Therefore, due to such inconsistencies found in literature, the subgroup analysis performed focused on identifying potential moderating factors explaining the dissimilar adaptations following CT.

Age and level

The present meta-analysis showed that the ESs for sprint and VJ adaptations following CT interventions were greater in younger players (<20 years), independent of the level of practice. It is possible that younger players had no sufficient strength training background, and for that reason any training stimulus would promote positive adaptations in performance, with or without PAP or combination of loads [26]. In fact, in the study by Brito et al. [37], in which

Fig 5. Standardized mean difference (SMD) in post-intervention VJ between CT-trained and control subjects. Squares represent the SMD* for each trial. Diamonds represent the pooled SMD across trials.

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Table 3. Subgroup analyses assessing potential moderating factors for sprint time and vertical jump height in studies included in the meta-analysis.

	Studies				Complex Training		
Group	Number[a]	References	SMD (95% CI)	*ES*	I^2	*P*	P_{Diff}
			Sprint				
Population characteristics							
Age							
≥20 years	4	[33, 34, 36]	-0.24 (-0.58, 0.09)	0.23	0	0.16	<0.05
<20 years	5	[35, 37, 41]	-1.33 (-2.02, -0.64)	1.13	43	<0.05	
Level							
Division 1	4	[34, 35]	-0.74 (-1.33, -0.15)	0.76	43	<0.05	<0.05
Under Division 1	5	[33, 36, 37, 41]	-0.74 (-1.57, 0.08)	0.70	72	0.08	
Exercise characteristics							
Frequency							
≥3 week^{-1}	2	[34]	-0.36 (-0.89, 0.16)	0.35	0	0.18	0.22
<3 week^{-1}	7	[33, 35, 36, 41]	-0.90 (-1.56, -0.23)	0.84	69	<0.05	
Intensity							
≥85% RM	3	[33, 34]	-1.07 (-1.82, -0.33)	0.25	70	<0.05	0.07
<85% RM	6	[35, 36, 41]	-0.27 (-0.73, -0.20)	0.96	0	0.26	
Duration							
≥6 weeks	6	[33, 35, 37, 41]	-1.06 (-1.82, -0.31)	0.95	63	<0.05	0.07
<6 weeks	3	[34, 36]	-0.29 (-0.65, 0.07)	0.29	0	0.12	
Total n° Sessions							
>12 sessions	4	[33, 34, 37]	-0.71 (-1.63, 0.20)	0.71	77	0.12	0.95
≤12 sessions	5	[35, 36, 41]	-0.75 (-1.33, -0.17)	0.74	43	<0.05	
			Vertical Jump				
Population Characteristics							
Age							
≥20 years	3	[33, 36, 39]	0.16 (-0.21, 0.54)	0.20	0	0.40	0.39
<20 years	5	[35, 38, 40]	0.45 (-0.09, 1.00)	0.42	21	0.10	
Level							
Division 1	5	[35, 38, 39]	0.21 (-0.23, 0.64)	0.2	0	0.35	0.50
Under Division 1	3	[33, 36, 40]	0.52 (-0.28, 1.33)	0.56	66	0.20	
Exercise characteristics							
Intensity							
≥85% RM	5	[35, 36, 38]	0.11 (-0.25, 0.48)	0.15	0	0.55	0.58
<85% RM	3	[33, 39, 40]	0.63 (-0.10, 1.35)	0.64	49	0.09	
Duration							
≥6 weeks	4	[33, 35, 40]	0.47 (-0.16, 1.10)	0.45	41	0.15	0.42
<6 weeks	4	[36, 38, 39]	0.16 (-0.21, 0.54)	0.22	0	0.39	
Total n sessions							
>12 sessions	2	[33, 40]	0.86 (-0.31, 2.02)	0.81	63	0.15	0.25
≤12 sessions	6	[35, 36, 38, 39]	0.15 (-0.18, 0.47)	0.18	0	0.37	
Intracomplex Rest							
≥2 minutes	4	[38–40]	0.58 (-0.01, 1.18)	0.55	24	<0.05	0.21
<2 minutes	2	[33, 36]	0.11 (-0.33, 0.55)	0.15	0	0.61	
Sport modality							
Jump predominance (Basketball/Volleyball)	4	[38–40]	0.58 (-0.01, 1.18)	0.55	24	0.05	0.18
Other Team-Sports	4	[33, 35, 36]	0.11 (-0.26, 0.48)	0.12	0	0.56	

Subgroup analyses are performed on SMD between post and pre-intervention sprint time and vertical jump in CT-trained groups. Median values of continuous variables were used as cut-off values for grouping studies. Changes in moderating factors were calculated as post-intervention minus pre-intervention values.

[a]Number of CT-Trained groups into this studies references. Certain enrolled studies were not included because the value used for subgroup analysis was not reported in them.

SMD, standardized mean difference; I^2, heterogeneity; ES, effect size; P, test for overall effect; P_{Diff}, test for subgroup differences.

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CT was compared to resistance training alone and plyometric only programs, no differences were found between protocols.

Concerning level of practice, D1 players showed slightly higher ES (ES = 0.76) than U-D1 (ES = 0.70) for sprint. Previous data [53] showed that increments in sprint level of practice. However, the positive medium effects obtained by both subgroups suggest that CT may be a suitable option to increase sprint performance independent of the athletes' level. As for VJ, U-D1 (ES = 0.42) and D1 players (ES = 0.20) presented small ESs, independent of age. It has been demonstrated that elite soccer players have higher percentages of fast muscle fibers compared to non-elite [54] and that strength levels [26, 55] and fiber type composition [56] may influence the magnitude of PAP, a possible mechanism contributing to performance gains with CT [18–20]. Also, it has been demonstrated that higher level athletes are better responders to PAP or CT programs [26, 55]. This contrasts with our findings regarding VJ, which may be possibly explained by the modest heterogeneity found in the U-D1 group, for this variable, indicating variability between the characteristics of the participants. However, reports of no differences being obtained, following CT acute protocols, among participants with dissimilar expertise, training background or strength levels have also been reported [27, 57].

Training frequency

No analysis of training frequency was conducted for VJ since all CT groups but one (CT1 [35]) performed 2 sessions/week. On sprint, results indicated that lower training frequencies (<3 week^{-1}) exhibited greater effects (ES = 0.84), than training 3 or more days. According to Seitz et al. [53], high resistance training frequencies may generate a greater stress, overwork and eventually impair performance, when performed concurrently with regular team practice. However, Seitz et al. [53] analyzed several resistance training programs and not only CT protocols. When considering solely CT, previous research [35, 41] indicated that a frequency of 2 or less times/week is as effective in increasing sprint performance as 3 or more sessions/week. Moreover, when a certain body part is actively used during competition or sport-specific training, lower weekly frequencies are needed to maintain performance levels [58].

Duration of intervention and total number of sessions

Concerning the duration of intervention, longer interventions were found to produce greater effects on sprint and VJ performance (sprint = 0.95; VJ = 0.45). This higher magnitude of effect in sprint seems to be in line with previous findings that stated that longer resistance-based interventions (>8 weeks) resulted in improved speed development in soccer as well as rugby and American football players [2]. In basketball players, no significant correlations were identified between program duration and increments in VJ following resistance training interventions [59]. However, it is worth noting that, on their respective reviews, both Bolger et al [2] and Sperlich et al. [59] referred to various resistance-based methods and not only to CT programs. On a practical perspective, the large effect (ES = 0.95) observed on sprint performance for programs over 6 weeks seem to indicate that, adaptation wise, longer CT program should be recommended. Also, 6 weeks of duration may be a good reference for strength and conditioning professionals in terms of program duration.

With respect to the number of sessions, for sprint, 12 or less CT sessions displayed a medium training effect (ES = 0.74), as well as performing over 12 (ES = 0.71). As for VJ, the opposite was observed with a shorter number of sessions resulting in lower ESs (ES = 0.18) than interventions consisting on more than 12 workouts (ES = 0.81). However, it is important to state that only 2 CT groups performed less than 12 sessions and that a modest heterogeneity (I^2 = 63) was found in this particular subgroup. Nevertheless, according to the data here obtained, less training sessions are needed to achieve performance improvements in sprint compared to VJ. In fact, it has been suggested that speed gains are greater when resistance training is combined with locomotor training [2]. All the participants included in the present meta-analysis were athletes currently competing in team-sports and so, apart from the CT protocols, players were engaged in sprinting actions during practice and or competition. Considering that sprinting activities are more frequent than jumping in basketball [8], rugby [5] and soccer [4, 51], it can be speculated that this is a possible rationale why, when CT is combined with regular team practice/competition, less sessions are necessary to elicit performance improvements in sprint when compared to VJ. However, further analysis of the influence of horizontally and vertically oriented exercises in CT may add valuable insight on how to maximize sprint or VJ post-intervention adaptations [60].

Intensity of the conditioning activity

With regards to the intensity of the CA, for both variables, intensities below 85% 1RM in the CA exhibited greater training effects (sprint = 0.96; VJ = 0.64) than maximal loads (>85% 1RM; sprint = 0.25; VJ = 0.15). The type of load of the CA influences the PAP response [22, 31]. Wilson et al. [31] reported that moderate intensities, ranging from 60% to 84% 1RM produced a significantly higher PAP response than loads heavier than 85% 1RM, independent of training experience or strength levels whereas Seitz and Haff [22] indicated that maximal loads elicited greater PAP responses. It seems that PAP may be mediated by the individual's strength level, since stronger athletes present higher PAP with maximal loads [22, 31, 55, 61, 62] while weaker subjects achieve it with sub-maximal loads [22]. It has been suggested that this occurs because when weaker individuals exercise with maximal loads, fatigue may exceed potentiation [22]. Theoretically, although PAP responses are highly individualized [20–22] and there is no clear agreement on its role as the main mechanism behind CT [24], a greater PAP could result in larger improvements on performance, following a CT protocol, if the explosive exercise was completed while the muscles were in a potentiated state [63]. With the data here obtained, it can be argued that the analyzed players' strength levels were not high enough for them to be able to achieve greater increments on VJ performance when heavy loads were utilized, and that is why larger training effects were elicited with loads lighter that 85% 1RM.

Intracomplex rest interval

Concerning the ICRI, a subgroup analysis was not possible to conduct for sprint performance. Two studies [35, 41] did not specify the rest between the CA and the subsequent exercise and from the remaining investigations [33, 34, 36, 37], just one presented a different rest interval [34]. For VJ, the ICRI ranged from <10 sec to 5 min. The data obtained showed that greater training effects were obtained with larger resting periods (ES = 0.55). This is in line with several studies [22, 27, 31] that have shown that the PAP response, although highly individualized, is larger when longer intervals are allowed between the CA and the subsequent explosive action. Seitz and Haff [22] indicated that rest intervals between 5 to 8 min exhibit larger PAP effects than ones ranging from 0.3 to 4 min. Nevertheless, it is worth noting that the studies reviewed by Seitz and Haff [22] were acute studies and not training interventions. This is an important aspect to consider, because when it comes to CT protocols composed by several sets of several complex pairs it is not practical to utilize ICRIs of 8 min, as the training session would take too long to be completed. Following a CA both potentiation and fatigue co-exist and the balance between these two responses is crucial if performance enhances are to be achieved [21, 22, 31]. Sale [64] identifies two dilemmas related to the PAP and fatigue responses after a CA. The first is that more intense CAs may lead to a higher potentiated state but also generate greater levels of fatigue. The second is that longer rest intervals may allow for a better recovery of fatigue but also result in a greater decrease of the PAP mechanism [64]. When it comes to designing a CT protocol it is necessary to find an adequate balance and to take into account that longer ICRIs are recommended but that in an everyday setting, recovery periods of 5–8 min may not be practical.

Team-sport modality

The influence of sport modality was analyzed only for VJ because it was possible to differentiate among sports where jumping actions are crucial for high performance (such as basketball [6] and volleyball [65]) and other modalities (soccer, rugby or baseball). Jump predominant sports exhibited medium effects (ES = 0.55) whereas non-predominant, only small (ES = 0.12). This may be related to the specificity of training background which is known to influence performance [66], or to the fact that during training and competition, a higher number of VJ are performed by basketball [6] and volleyball [65] players in comparison to other sports [50] and that this specific stimulus lead to medium effects in the magnitude of improvement in VJ.

Regarding sprint, however, from the 9 CT intervention groups analyzed, 6 consisted on soccer players [35, 37, 41], 2 on rugby players [37] and one on baseball athletes [36]. For this reason, a subgroup analysis was not performed, as there was no modality in which sprint could be considered more crucial to performance than others.

Limitations

Some limitations can be identified within the present meta-analysis. First, the scarce number of studies included, due to the few publications on CT interventions on team-sports that have sprint or VJ as an outcome variable. Second, not all analyzed CT programs were compared to a CG or to other training methods aimed at developing strength and/or power. Moreover, the heterogeneity in athlete characteristics (age, level, training history) is another factor that should be taken into account and that may be considered a limitation. Also, the training mechanisms outside the CT interventions were not considered in the analysis, as well as the resistance training protocols performed in the weeks prior to the CT programs. Finally, different methodological procedures and instruments were used to assess performance (VJ, particularly) in the different studies. Hence, it cannot be ruled out that some outcome values may have been affected by the method used.

Conclusions and practical applications

CT is a training method aimed at developing both strength and power, which has a direct effect on sprint and VJ performance. When outlining the season planning for team-sports, strength and conditioning professionals should take into consideration that this may be a suitable method as it produces medium training effects on sprint performance and small positive effects on VJ.

Although the response to CT is highly individualized, based on the present results, programs lasting over 6 weeks, with a frequency of 2 sessions/week and CA activities with loads lighter than 85% 1RM seem to be the most adequate to improve sprint performance. Regarding VJ, CT protocols with a duration of more than 6 weeks, with 12 or more total sessions, CA activities below 85% 1RM and ICRI longer than 2 min appear to be the most effective on team-sport athletes. Finally, players from sports in which jumping actions are more frequent and crucial for high performance (basketball/volleyball) seem to benefit the most from CT.

Supporting information

S1 Table. PRISMA checklist.
(DOC)

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Writing – review & editing: Alejandro Martinez-Rodriguez, Julio Calleja-González, Pedro E. Alcaraz.

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APPENDIX 3. Study 3: SHORT-TERM OPTIMAL LOAD TRAINING VS A MODIFIED COMPLEX TRAINING IN SEMI-PROFESSIONAL BASKETBALL PLAYERS

Reference:

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Short-term optimal load training vs a modified complex training in semi-professional basketball players

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ABSTRACT
This study investigated the effects on neuromuscular performance of a 6-week Optimal Load Training (OLT) and a novel modified Complex Training (MCT) (complex pairs: the same exercise using a moderate and an OL) in basketball players, in-season. Eighteen male athletes were randomly assigned to one of the protocols. Anthropometric measurements were taken to evaluate body composition. Lower- and upper-body maximum dynamic strength, countermovement jump (CMJ), standing long jump (SLJ), 10-m sprint and change of direction (COD) were also assessed. Moderate-to-large strength gains (presented as percentage change ± 90% confidence limits) were obtained for half-squat (OLT: 10.8 ± 5.3%; MCT: 17.2 ± 11.6%) and hip thrust (OLT: 23.5 ± 17.7%; MCT: 28.2 ± 19.0%). OLT athletes achieved *likely small* improvements in sprint (1.6 ± 1.6%) and COD (3.0 ± 3.2%). Players in the MCT attained *likely moderate* improvements in COD (3.0 ± 2.0%) and *possibly small* in SLJ (2.5 ± 4.6%). No protocol relevantly affected CMJ or body composition. An ANCOVA test revealed *unclear* between-group differences. In conclusion, both protocols increased basketball players' strength without the use of heavy loads (> 85% 1RM) and without impairing sprint, CMJ and SLJ performance. These findings suggest that basketball strength and conditioning professionals may use either method to counteract strength losses during the season.

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Strength; power; jump; squat; bench press

Introduction

Basketball is a sport that incorporates aerobic and anaerobic metabolic processes and it is characterized by intermittent high-intensity explosive actions such as: jumping, sprinting or changing of direction (Narazaki, Berg, Stergiou, & Chen, 2009). According to the literature, maximal power is crucial in most sports-specific movements (Cormie, McGuigan, & Newton, 2011), particularly in basketball (Wen, Dalbo, Burgos, Pyne, & Scanlan, 2018), in which vertical jump and agility, actions that require substantial power production, are determinants of high performance (Delextrat & Cohen, 2008; Ziv & Lidor, 2009). Furthermore, maximal power, along with strength, has been shown to differentiate competition levels among basketball players (Ziv & Lidor, 2009). Therefore, applied research on training programs designed to improve strength and power without the use of heavy loads is of great interest for sport scientists and practitioners.

During the season, different resistance training methods are prescribed to improve athletic performance in team-sports (Freitas, Martinez-Rodriguez, Calleja-González, & Alcaraz, 2017; Hermassi, Chelly, Tabka, Shephard, & Chamari, 2011; Loturco et al., 2016a; Manzi et al., 2010). Amongst the several methodologies, Optimal Load (OLT) and Complex Training (CT) are two training protocols that are becoming increasingly popular within the strength and conditioning and scientific communities, as supported by recently published meta-analyses (Freitas et al., 2017; Soriano, Suchomel, & Marín, 2017).

In OLT, athletes perform a given exercise with the load that maximizes its mechanical power (Cormie et al., 2011; Soriano et al., 2017). This load is usually determined as a percentage of the 1-repetition maximum (RM) or percentage of body mass (Alcaraz, Romero-Arenas, Vila, & Ferragut, 2011; Soriano et al., 2017) and it has been reported to provide the best stimulus for power enhancement (Balsalobre-Fernández, Tejero-González, Campo-Vecino, & Alonso-Curiel, 2013; Cormie et al., 2011; Loturco et al., 2016a; Soriano et al., 2017). Moreover, this method has been suggested to result in the greatest increments in dynamic athletic performance (Wilson, Newton, Murphy, & Humphries, 1993).

The load that maximizes power output is exercise-specific and the same relative intensity cannot be applied to all exercises (Izquierdo, Häkkinen, González-Badillo, Ibanez, & Gorostiaga, 2002; Soriano et al., 2017). Firstly, each exercise has unique biomechanical and neurophysiological characteristics that influence power output (Soriano et al., 2017). Secondly, an athlete's training background influences muscle mechanics, cross-sectional area or fiber type distribution, which is known to affect power production (Izquierdo et al., 2002). In a recent study, Loturco et al. (2016a) reported that 6 weeks of OLT resulted in improved 10 m and 20 m sprint times and power production when compared to a classic

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strength-power periodization in soccer players. These promising results seem to indicate that OLT may be a suitable option to apply in team-sports, although further research is necessary.

CT is a method that combines, set by set in the same session, biomechanically similar (comparable kinematics) high-intensity resistance exercises with plyometric or power exercises, performed at maximal movement velocities (Ebben, 2002; Ebben & Watts, 1998). A back squat followed by a countermovement jump (CMJ) is an example of a complex pair, the term used to describe two consecutive exercises combined (Ebben, 2002; Ebben & Watts, 1998). The mechanisms underlying the adaptations following CT are still unclear. On the one hand, it has been suggested that high-intensity resistance exercises increase motoneuron excitability and reflex potentiation, creating enhanced training conditions for subsequent neuromuscular power adaptations (Ebben & Watts, 1998). On the other, postactivation potentiation (PAP), a phenomenon characterized by an acute muscle force or power output enhancement after a maximal or near-maximal contraction (Tillin & Bishop, 2009), is believed to be responsible for performance improvements following CT (Carter & Greenwood, 2014; Freitas et al., 2017). Greater PAP responses have been reported to occur in stronger athletes, when high-intensity resistance exercises are performed (≥ 85% of 1RM) and after longer recovery intervals (> 5 min) between the conditioning activity and the subsequent athletic task (Seitz & Haff, 2016). However, the latest evidence regarding team-sports suggest that heavy loads may not be the most appropriate to elicit PAP (Dello Iacono & Seitz, 2018), or to be used in CT interventions (Freitas et al., 2017). This type of loading can negatively affect the fatigue-PAP relationship, leading to higher levels of transient fatigue and lesser potentiation (Tillin & Bishop, 2009).

A recent meta-analysis investigated the short-term adaptations following CT in team-sports (Freitas et al., 2017) and reported positive training effects on sprint and vertical jump performance. However, it remains unclear if CT is more effective than other training programs designed to improve strength and power in trained athletes (Freitas et al., 2017; Lim & Barley, 2016). Moreover, it is still unknown how modifying the characteristics of CT programs may affect performance. Current literature suggests that, individually, both OLT and CT are methods likely leading to performance improvements in team-sports. However, to the best of our knowledge, no previous investigations have addressed their combined effects within a CT protocol during a basketball competitive season. Given the potential benefits reported when employing OL in team-sports (Loturco et al., 2016a), we considered relevant to investigate how a CT consisting on a moderate intensity conditioning activity followed by an exercise performed with a load that maximizes power output might influence neuromuscular adaptations.

Therefore, the aims of this research were: (1) to investigate the effects of an OLT and a novel modified CT (complex pairs consisting on the same exercise performed with a moderate (80% of 1RM) and an individually determined OL) on neuromuscular performance in basketball players; (2) to compare their effects after a 6-week intervention.

Methods

Study design

A quasi-experimental, short-term (6-week intervention and 2-week testing) study was conducted. Intra- and inter-participants differences were analysed in a pre- and post-test design. Players were matched by playing position (guards, forwards and centres) and, then, randomly assigned (Research Randomizer Software 4.0; Lancaster, Pennsylvania) to one of two training protocols: Optimal Load training (OLT) or a modified Complex Training (MCT). During the intervention period (competitive phase of the 2016/2017 season), participants played 7 official games and participated on 24 basketball practices. With the coaches' agreement, the microcycle planning was similar during the 8-week period. Basketball training was prescribed by the coaching staff and consisted mainly on small-sided basketball games, 5 × 5 scrimmage, shooting and fast-break drills. Internal load was monitored with the session rating of perceived exertion (Moreira, McGuigan, Arruda, Freitas, & Aoki, 2012) and kept constant during the research period, with *very likely* trivial differences identified between training groups (an average total weekly training load of 2316 ± 191 and 2303 ± 211 AU for OLT and MCT, respectively).

Participants

Initially, 23 semi-professional male basketball players competing in Spanish League EBA (4th Division), with at least 8 years of playing experience and 1-year participation in resistance training, volunteered to participate. No player sustained any severe injury in the 2 years prior to the study and no disease or medication intake was reported during the intervention. Players were fully informed about the procedures and signed a written consent approved by the local Ethics Committee in accordance with the Helsinki Declaration (General Assembly of the World Medical Association, 2014). All participants underwent a physical examination by the team physician and were cleared of any endocrine disorders that might limit their ability. They were instructed to maintain their normal diet habits and their team´s regular practice schedule (4 training sessions per week). During the intervention, two players were promoted to the club's professional team and three sustained injuries unrelated to the training protocols. Therefore, a total of 18 players (age: 21.3 ± 4.3 years, height: 194.5 ± 11.4 cm, body mass: 90.9 ± 14.8 kg) were included in the statistical analysis, as they completed at least 85% of the total number of sessions.

Testing procedures

Testing was completed in a research centre and at each team's pavilion (temperature: 21-23° C, humidity: 57–61%). Procedures were carried out in two separate days, after 36 h of rest. On day 1, players reported to the research centre at 10:00 and completed the following sequence: (1) anthropometric measurements; (2) warm-up; (3) maximum dynamic strength and power-load profiling in half-squat, bench press and hip thrust. The exercise order was randomized for each player, with the condition that the bench press was always the second exercise, to avoid performing two lower-body exercises consecutively. Warm-up consisted on 8 min treadmill running, followed by dynamic stretching, core and lower-body activation drills. On day 2, in the pavilion, procedures were: (4) warm-up; (5) CMJ and standing long jumps (SLJ); (6) 10 m sprint and (7) T-test. The testing sequence was randomized for each player. Warm-up involved the same exercises as in day 1, with the addition of accelerated running drills with and without COD. After the 6-week protocols, procedures were repeated following the exact same methods. For all tests performed, within-session test-retest reliability was assessed by the coefficient of variation (CV).

Anthropometric measurements

The same researcher (ISAK Level-1 certified) performed the anthropometric measurements, in both pre- and post-test. Height, body mass, circumferences and skinfold thickness were determined for each player. The relaxed and flexed arm, waist, hip and leg circumferences were measured twice with a 2 m measuring tape (CESCORF, Porto Alegre, Brazil) and the average of the two values was taken. The skinfold thickness was assessed in accordance with ISAK guidelines (Lohman, Roche, & Martorell, 1988) using a set of Harpenden Skinfold Calipers (Baty International, West Sussex, UK). Eight skinfolds were measured: biceps, triceps, subscapular, iliac crest, supraspinal, abdominal, anterior thigh, and medial calf. All skinfolds were determined three times and the average of the measurements was considered as the true skinfold thickness (intra-rater CV = 0.75%). Percentage of body fat was estimated with the Faulkner Equation (Faulkner & Falls, 1968) and percentage of muscle mass with the modified Matiegka equation (Drinkwater & Ross, 1980). The sum of the eight skinfolds was also determined.

Maximal dynamic strength

Maximal dynamic strength was assessed for both lower and upper limbs by estimating the half-squat, bench press and hip thrust 1RM. All exercises were performed on a modified Smith machine with a linear encoder (Chronojump-BoscoSystem, Spain) attached to the barbell, interfaced with a computer. All data were recorded with the Chronojump-BoscoSystem Software. Before the testing, participants executed two warm-up sets with a submaximal load that allowed them to complete 8–10 repetitions. Then, to estimate the half-squat 1RM, players executed 3 repetitions with their perceived 4-6RM (based on their previous experience and training loads). They were asked to descend to a position of 90° of knee flexion, and were verbally encouraged to move the barbell as fast as possible in the concentric phase. The mean propulsive velocity (MPV) of each repetition was recorded, and the highest value was used to estimate the 1RM. Since a very strong linear relationship has been reported between the MPV and the percentages of the half-squat 1RM, the estimated 1RM (CV = 2.7%) was calculated (Loturco et al., 2016b):

$$\%\ Half - Squat\ 1RM = -105.05 \times MPV + 131.75$$

For the bench press, similar procedures were followed. The barbell was lowered to the point where it nearly touched the chest and the concentric phase was performed at maximal velocity. The 1RM was estimated (CV = 2.2%) based on the theoretical load at zero velocity and the average velocity (AV) of the bar (Jidovtseff, Harris, Crielaard, & Cronin, 2011):

$$\%\ BenchPress1RM = \frac{AV - 1.7035}{-0.0146}$$

For the hip thrust, the 1RM was determined following traditional guidelines (Haff & Triplett, 2015), as no equation that allowed an accurate prediction of the maximum dynamic strength in this exercise was found on literature. Spotters were present to assist in racking the resistance and to ensure that participants maintained a consistent and safe technique, in line with the guidelines presented by Contreras, Cronin, and Schoenfeld (2011).

Power-load profiling

Power-load profiles were calculated for the half-squat, bench press and hip thrusts using the relative intensity corresponding to 30%, 45%, 60% and 75% of the previously estimated 1RM, to determine the intensity that maximized power output using the same lineal encoder. Players completed 3 repetitions with each load, performing a 3 s eccentric phase followed by a maximal velocity concentric phase. Peak power was recorded for each repetition and the load corresponding to its highest value was considered for the training protocols. A 3 min rest was allowed between trials.

Standing long jump

The SLJ was performed as described elsewhere (Markovic, Dizdar, Jukic, & Cardinale, 2004). Participants performed two practice trials and then two test trials separated by 1 min rest. The horizontal distance was measured to the nearest 0.01 m (CV = 2.5%). Only the best result was considered for analysis. This test has been recommended for basketball players' assessment (Calleja-González et al., 2016).

Countermovement jump

The CMJ was performed on a Kistler 9286BA portable force platform (Kistler Group, Winterthur, Switzerland) following the protocol described in previous research (Markovic et al., 2004). The depth of the countermovement was self-selected and players were asked to land close to the point of take-off. Two submaximal trials and two maximal CMJ were performed, with 1 min rest. The attempt with the highest jump height, based on the take-off velocity, was considered (CV = 3.5%). Raw data was exported and jump height, height and absolute peak power were calculated with Microsoft Excel (Microsoft Corporation, Redmond, WA, USA).

10 m sprint

The 10 m sprint test, recommended for basketball players' assessment (Delextrat & Cohen, 2008), was performed on the court with basketball shoes. Participants stood 0.3 m behind the starting line and, at investigator's signal, completed a maximal all-out straight line 10 m sprint, starting from a two point stance. Time was measured with wireless photocells (WITTY System, Mircrogate, Bolzano, Italy) placed on the starting and finish lines, 1 m above ground level (Delextrat, Trochym, & Calleja-Gonzalez, 2012). Each player was allowed two trials, separated by 2 min rest (CV = 3.4%).

T-test

The T-Test was performed following the standard procedures described elsewhere (Sekulic et al., 2017). Since there is no external stimulus or decision making skills, this test assesses change of direction (COD) speed. Time was measured with wireless photocells placed on the starting line, 1 m above ground level. Participants started the test on a two point stance and were verbally encouraged throughout to perform maximal effort. The only parameter considered was total time. Two trials were allowed (CV = 1.5%), separated by 2 min, and the best time was considered.

Training protocols

The training protocols were performed two times per week and lasted 6 weeks. Both the OLT and MCT consisted of 3 exercises: half-squat, bench press and hip thrust. The characteristics of each program are presented in Table 1 and the weekly load progression in Table 2. The combination of 80% of 1RM + OL, applied in the MCT, was based on previous findings that reported that CT protocols with loads below 85% of 1RM seem to be the most effective in team-sports (Freitas et al., 2017). The total number of sets and repetitions were the exact same for both training groups. On week 4, loads were adjusted during the first set of each exercise (half-squat and hip thrust on the first session of the week and bench press on the second), by estimating the 1RM based on barbell velocity, as previously described.

Statistical analyses

Data are presented as mean ± SD. Descriptive statistics were calculated using SPSS 21.0 (IBM SPSS Inc., Chigaco, IL, USA).

Table 1. Characteristics of the training protocols.

	Load	ICRI	Recovery
Modified Complex Training			
Half-Squat + Half-Squat (OL)	80% 1RM + OL	2 min 30 s	3 min
Bench Press + Bench Press (OL)	80% 1RM + OL	2 min 30 s	3 min
Hip Thrust + Hip Thrust (OL)	80% 1RM + OL	2 min 30 s	3 min
Optimal Load Training			
Half-Squat	OL	N/A	3 min
Bench Press	OL	N/A	3 min
Hip Thrust	OL	N/A	3 min

ICRI = intracomplex rest interval; OL = optimal load; 1RM = 1 repetition maximum; N/A = not applicable.

Normality was assessed with the Shapiro-Wilk test, the homogeneity of variances with the Levene test. To compare the effects of both experimental protocols, an ANCOVA test was performed in SPSS 21.0, with baseline values as covariates.

Pre-post effect sizes (ES) were calculated using Cohen's equations (Cohen, 1977). Between-group ES were determined by converting the partial eta-squared from the ANCOVA output to Cohen's d. Threshold values for ES statistics were: > 0.2 small, > 0.6 moderate, and > 1.2 large (Hopkins, Marshall, Batterham, & Hanin, 2009).

To make inferences about the true values of the effect on the selected variables, 90% confidence intervals (CI) were used. The likelihoods that the true value of the effect represented substantial changes (positive or negative) were calculated using a customized spreadsheet (Hopkins, 2007). For the between-group analysis, the same spreadsheet was used to convert the ANCOVA p-values and the effect statistic to magnitude-based inferences. An effect was considered unclear if its CI simultaneously overlapped the thresholds for positive and negative or if the chances of the effect being substantially positive and negative were both > 5% (Hopkins et al., 2009). Percentage change was derived from the log transformed data within the spreadsheet used for analysis.

To our knowledge, in basketball, there is no evidence of direct performance benefits or direct relationship between team and test performance on the tests performed in this study, as it occurs with other sports (Haugen, Tønnessen, Hisdal, & Seiler, 2014). Therefore, an effect was considered relevant when its ES ≥ 0.2, as suggested for team-sports (Hopkins, 2004).

For the variables in which a decrease in the mean represented a positive outcome (% of body fat, total time in T-test and 10 m sprint) the negative standardized change was multiplied by −1 for the graphic representation of the data, as it could be considered a positive effect. The qualitative terms and the default values were: most unlikely, < 0.5%; very unlikely, 0.5–4.9%; unlikely, 5–24.9%; possibly, 25–74.9%; likely, 75–94.9%; very likely, 95–99.5%; and most likely, > 99.5% (Hopkins, 2007).

Results

Pre-post mean ± SD, percentage change in the mean and ESs for the OLT and MCT are shown in Table 3. Chances that each protocol presented a positive/trivial/negative effect and the respective inferences are displayed on Figure 1.

Table 2. Weekly progression of the training load.

	Weeks 1–2		Weeks 3		Week 4–5		Weeks 6	
	Sets	Reps	Sets	Reps	Sets	Reps	Sets	Reps
Modified Complex Training								
Half-Squat + Half-Squat (OL)	3	3 + 4	3	3 + 5	4	3 + 4	3	3 + 4
Bench Press + Bench Press (OL)	3	3 + 4	3	3 + 5	4	3 + 4	3	3 + 4
Hip Thrust + Hip Thrust (OL)	3	3 + 4	3	3 + 5	4	3 + 4	3	3 + 4
Total	**9**	**21**	**9**	**24**	**12**	**21**	**9**	**21**
Repetition-Volume	189		216		252		189	
Optimal Load Training								
Half-Squat	3	7	3	8	4	7	3	7
Bench Press	3	7	3	8	4	7	3	7
Hip Thrust	3	7	3	8	4	7	3	7
Total	**9**	**21**	**9**	**24**	**12**	**21**	**9**	**21**
Repetition-Volume	189		216		252		189	

Reps = repetitions; OL = optimal load.

Table 3. Body composition, strength and performance measurements for all variables on both experimental conditions.

	Optimal Load Training				Modified Complex Training			
	PRE	POST	% Change (± 90% CL)	ES (± 90% CL)	PRE	POST	% Change (± 90% CL)	ES (± 90% CL)
Body Composition								
Muscle Mass (kg)	45.14 ± 5.22	46.04 ± 5.06	2.2 (± 3.8)	0.16 (± 0.37)	43.7 ± 6.6	42.6 ± 6.2	−2.3 (± 5.6)	0.14 (± 0.80)
8 Skinfold Sum (mm)	79.2 ± 21.6	75.4 ± 20.2	−4.4 (± 8.0)	0.16 (± 0.28)	79.5 ± 23.7	78.4 ± 21.0	−0.03 (± 8.3)	0.04 (± 0.09)
Body Fat (%)	12.3 ± 2.0	12.0 ± 1.8	−2.1 (± 4.7)	0.13 (± 0.23)	12.2 ± 1.8	12.08 ± 1.7	−1.1 (± 1.9)	0.06 (± 0.1)
Strength								
Half-Squat 1RM (kg)	149.1 ± 23.0	165.4 ± 27.9	10.8 (± 5.3)	0.64 (± 0.36)	154.8 ± 33.3	178.2 ± 14.5	17.2 (± 11.6)	0.64 (± 0.47)
Bench Press 1RM (kg)	76.4 ± 14.2	78.2 ± 15.0	2.2 (± 3.7)	0.11 (± 0.15)	66.6 ± 14.8	69.2 ± 13.2	4.3 (± 4.6)	0.15 (± 0.17)
Hip Thrust 1RM (kg)	144.2 ± 32.2	179.0 ± 46.4	23.4 (± 17.7)	0.98 (± 0.72)	145.7 ± 29.9	186.6 ± 39.6	28.2 (± 19)	1.23 (± 0.71)
Performance								
CMJ Height (cm)	36.5 ± 7.2	37.9 ± 7.5	4.0 (± 3.8)	0.17 (± 0.14)	36.4 ± 4.2	37.2 ± 3.6	2.2 (± 4.3)	0.15 (± 0.31)
CMJ Peak Power (W)	4699.1 ± 780.5	4833.1 ± 762.5	2.9 (± 3.5)	0.16 (± 0.11)	4594.2 ± 730.0	4775.3 ± 712.4	3.0 (± 4.4)	0.22 (± 0.21)
SLJ Distance (m)	2.27 ± 0.22	2.27 ± 0.24	−0.72 (± 9.0)	0.01 (± 0.2)	2.39 ± 0.23	2.46 ± 0.24	2.5 (± 4.6)	0.27 (± 0.24)
10m Sprint Time (s)	1.91 ± 0.09	1.87 ± 0.09	−1.63 (± 1.6)	0.29 (± 0.22)	1.89 ± 0.10	1.86 ± 0.13	−2.3 (± 4.6)	0.27 (± 0.56)
T-Test Time (s)	9.71 ± 0.67	9.46 ± 0.30	−3.03 (± 3.2)	0.42 (± 0.24)	9.45 ± 0.35	9.16. ± 0.50	−3.0 (± 2.1)	0.75 (± 0.6)

Data are shown as mean ± SD. OLT = Optimal Load Training; MCT = Modified Complex Training; ES = Effect Size; CL = Confidence Limits; RM = Repetition Maximum; CMJ = Countermovement Jump; SLJ = Standing Long Jump.

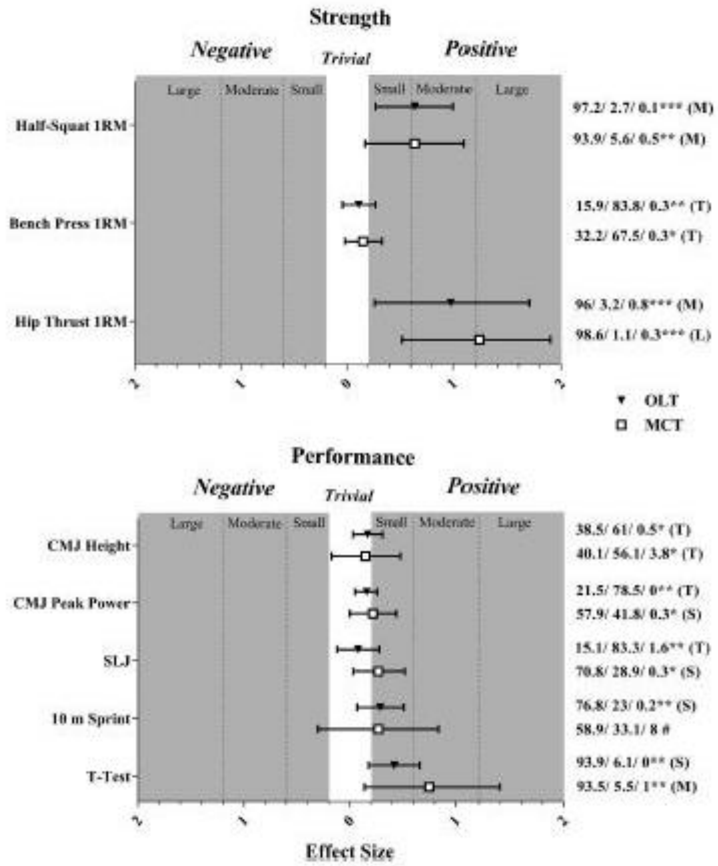

Figure 1. Changes in strength (A) and performance variables (B) in both training protocols. For the variables in which a decrease in the mean represented a positive outcome (total time in T-test and 10 m sprint) the negative standardized change (ES) was multiplied by −1 for the graphic representation of the data. The numbers represent the chance of the true value having positive/trivial/negative effect. T = trivial; S = small; M = moderate. #unclear; *possibly; **likely; ***very likely.

Regarding the OLT, *very likely moderate* improvements were observed for half-squat and hip thrust 1RM. *Likely small* improvements were attained for 10m sprint and COD. For bench press, SLJ and CMJ peak power, *likely trivial* effects were found. Finally, for CMJ height, *possibly trivial* effects were observed. Considering the MCT protocol, *very likely large* adaptations occurred for hip thrust. *Likely moderate* effects were displayed for half-squat and COD; and *possibly small* effects for CMJ peak power and SLJ. *Possibly trivial* effects were obtained for bench press 1RM and CMJ height. For sprint, *unclear* effects were found.

Between-group analyses are shown in Figure 2. After controlling for baseline differences, all comparisons were deemed *unclear* except for SLJ, in which *likely moderate* ES favouring MCT were obtained.

Discussion

The aims of this research were to investigate basketball players' strength and power adaptations following an OLT and a novel MCT intervention, and to compare their effects after a 6-week program. The main finding was that both protocols, performed alternatively with basketball training, increased lower-body strength in-season, without impairing the main physical performance variables (sprint, CMJ, SLJ and COD). This is very relevant for sport scientists and practitioners given that previous research has shown that significant strength losses occur in college-aged players during the course of a basketball season (Caterisano, Patrick, Edenfield, & Batson, 1997).

Concerning lower-body strength, both training groups displayed moderate-to-large improvements in half-squat and hip thrust 1RM, supporting previous research that reported dynamic strength gains in athletes following OLT (Balsalobre-Fernández, et al., 2013; Loturco et al., 2016a) or CT (Brito, Vasconcellos, Oliveira, Krustrup, & Rebelo, 2014; Faude, Roth, Di Giovine, Zahner, & Donath, 2013; Kobal et al., 2017). Our data indicated increases of 17.2% and 10.8% for the MCT and OLT groups, respectively, in the half-squat exercise. The 17.2% improvement achieved by MCT group may be explained by the fact that the players in this program completed 3 of the 7 total reps in each set with 80% of 1RM, hence lifting heavier loads each session (greater volume of higher intensity loads). Concerning the OLT group, athletes were able to achieve a higher acceleration of the barbell for all repetitions, therefore applying a considerable amount of force (force equals mass multiplied by acceleration), which may account for the strength gains (Loturco et al., 2016a).

It has been recommended that training for maintaining or increasing strength throughout the season is important for basketball players (Ziv & Lidor, 2009). Moreover, a review by Suchomel, Nimphius, and Stone (2016) concluded that greater muscular strength is associated with enhanced general sport skill performance and to a greater robustness and reduced risk of injury, which highlights the practical relevance of the present findings.

Regarding upper-body strength, bench press 1RM was not substantially affected in either group, as demonstrated by the trivial ES obtained with increases of 2.2% in OLT and 4.3% in MCT. This finding is in contrast with Sarabia, Moya-Ramón, Hernández-Davó, Fernandez-Fernandez, and Sabido (2017) that investigated the effects of an OLT and a traditional power training (50% of the maximum number of possible repetitions) in recreationally active participants and reported significant increases in bench press 1RM of 10.6% and 14.5%, respectively. However, a direct comparison among results is difficult due to the differences in the training programs, the duration of intervention and sample characteristics. Interestingly, we found positive meaningful effects for lower-body strength but not for upper-body. Two lower limbs exercises were performed, while only one was prescribed for upper-body, suggesting that the training volume for the upper-body was too low to generate adaptations in athletes with previous experience in bench press (Peterson, Rhea, & Alvar, 2004), such as basketball players. We can hypothesize that applying the same stimulus (same repetition and loading scheme) for all exercises and muscle groups was not appropriate to elicit positive adaptations in both upper and lower-body.

Concerning vertical jump ability, both protocols attained trivial effects in CMJ. In light of the results reported on the meta-analysis by Freitas et al. (2017), an increase CMJ height could be expected following MCT, which did not occur. The absence of jumping/plyometric exercises during the intervention may have hindered specific adaptations in the high-velocity zone of the force-velocity relationship (Loturco et al., 2017). Loturco et al. (2016a) reported a 11.5% increase in CMJ height following a OLT intervention with elite soccer players whereas, in our study, a 4% increment was obtained for the OLT group. The substantial differences between programs may account for such disparities. First, Loturco et al.'s (2016a) soccer players completed 18 sessions during the intermission period (no official games were played) whereas, in the present study, players completed 12 sessions, in-season. Second, in Loturco et al. (2016a) study, players performed jump squats instead of half-squat and hip thrust. Jump squat has been shown to be more connected to jump abilities in team-sports athletes than half-squat, since there is no breaking phase in the former exercise (Loturco et al., 2017).

Given that the basketball players in this research had previous experience in strength/power training, a plateau effect might have been achieved prior to the intervention. This advocates that the training stimulus was not appropriate to elicit relevant adaptations in CMJ and that there was a reduced transfer between the strength gains observed and vertical jump performance. To maximize the transference of power training to performance, training must include movement patterns, loads and velocities that are specific to the demands of the sport (Cormie et al., 2011), which was not the case in this study.

Regarding SLJ, a moderate ES favouring the MCT group was observed (Figure 2). This greater effect may be explained by the large strength gains in the hip thrust exercise in which there is a notable application of horizontal force (Contreras et al., 2011), similarly to the SLJ.

Sprint performance was *likely* positively affected in the OLT group but the effects of the MCT protocol were *unclear*. The MCT showed a 58.9% chance of having a positive effect on sprint, but also an 8% likelihood of having a negative impact. In the present research, small ES were obtained for a distance of 10 m for OLT and MCT, with the latter group presenting a substantially wider CL. Freitas et al.'s (2017) meta-analysis reported a moderate increase on sprint performance (ES = 0.73) following CT interventions in team-sports athletes, over distances between 15 and 30 m. However, in the studies included, CT incorporated plyometric or

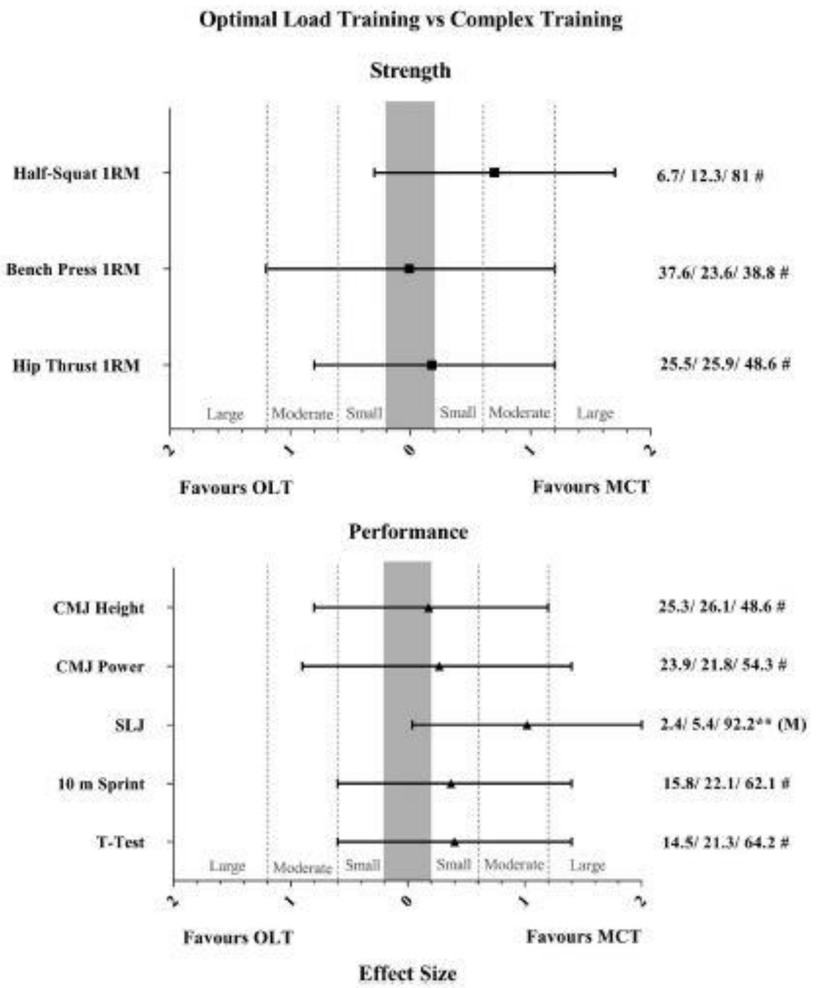

Figure 2. Optimal Load Training vs Modified Complex Training- Difference in the changes between protocols in strength (A) and performance variables (B), after controlling for baseline values. The numbers represent the chance that the true effect favoured OLT/was trivial/favoured MCT. The grey area represents trivial effects. M = moderate. #unclear; **likely.

ballistic exercises, allowing greater movement velocities to be achieved in the complex pairs, as a result of the absence of a braking phase (Loturco et al., 2017).

It is important to highlight that ours is the first research to investigate the effects of a MCT protocol in which the complex pairs consisted on the same exercise performed with a moderate and an OL. It may be that this type of loading is not as effective as the traditional CT initially proposed by Ebben and Watts (1998), that utilized higher velocity exercises (CMJ, short sprints, medicine ball throws, etc). In addition, our intervention was applied during the competitive phase of the season and a ceiling effect may have been previously reached by the athletes (Faude et al., 2013). Therefore, in the absence of specific sprint or acceleration training in both protocols, only small effects were achieved. Regarding OLT, Loturco et al. (2016a) reported a significant improvement (7.1%) in 10 m sprint performance following a 6-week intervention period, while our study only obtained an increase of 1.6%. As stated before, the dissimilarities between programs may help explain the higher increments reported elsewhere (Freitas et al., 2017; Loturco et al., 2016a).

COD ability, measured with the T-Test, was *likely* positively affected following both protocols. This finding supports previous research regarding OLT (Loturco et al., 2016a) but is in contrast with most literature on CT, which found no relevant effects on COD performance in team-sports (Brito et al., 2014; Faude et al., 2013; Kobal et al., 2017). Interestingly, large effects on hip thrust 1RM and small on SLJ were achieved in MCT, and moderate and trivial were displayed in the OLT group on the same exercises, characterized by a prominent application of horizontal force (Contreras et al., 2011). In the T-Test, the distances covered are short and several COD are performed. Hence, the ability to accelerate and decelerate plays an important role. Given that in accelerated running, the application of horizontal forces is crucial (Rabita et al., 2015), the improvements observed in SLJ distance and hip thrust 1RM may account for the results attained.

Moreover, it has been suggested that increases in maximal strength are more likely to increase sprint performance at short distances (5 m) (Comfort, Bullock, & Pearson, 2012), when acceleration plays the most important role, as it occurs in the T-Test. Nevertheless, more research is warranted on COD ability. Finally, regarding body composition, trivial effects were obtained in both training groups, indicating that no changes were observed in body fat or muscle mass during the intervention period.

When comparing the effects of the two interventions, it was *unclear* which program resulted in higher adaptations. This outcome suggests that the measures used were not sensitive enough to detect a clear effect with the sample size analysed. Concerning OLT, different studies comparing this method to traditional strength training interventions found similar results (Loturco et al., 2016a; Loturco, Ugrinowitsch, Roschel, Tricoli, & González-Badillo, 2013). No differences were reported between training protocols in the relative changes in back squat 1RM, CMJ and 20 m sprint (Loturco et al., 2013) or COD speed in soccer players (Loturco et al., 2016a). With respect to CT, Brito et al. (2014) found it was equally effective in increasing muscular strength and sprint performance when compared to traditional resistance training. The overall similar adaptations following OLT and MCT may be due the high neuromuscular demand of both protocols along with the intention of moving the loads as fast as possible in every workout session. However, we cannot exclude that the basketball training/competition stimulus may have contributed to the observed adaptations.

Some limitations need to be addressed. Firstly, the small sample size prevented us from identifying clear between-group effects, as shown by the large CIs. Secondly, as no control group was present, it was not possible to determine the influence of the basketball training sessions on the adaptations reported. We can only conclude that the training interventions combined with the basketball-specific stimulus led to these outcomes. Finally, adaptations to CT programs have been suggested to be highly individualized (Freitas et al., 2017) but, in the present research, the intracomplex rest interval and the intensity of the conditioning activity were similar to all players because it would not be practical, in a team-sports setting, to individually adjust rest periods. Nevertheless, training was individualized in the sense that all players trained within their own specific optimal power zone in both OLT and MCT. Despite these limitations, it is worth noting that this study was delivered in a real sporting setting, where athletes perform several concurrent activities, and within the constraints of limited time and resources, typical in this type of applied research (Bishop, 2008).

In conclusion, this study investigated the effects of two different resistance training protocols aimed at developing strength and power. Similar adaptations were achieved following OLT and MCT in basketball players. Strength gains obtained were moderate-to-large for lower-body exercises but trivial for upper-body. Athletes in the OLT group achieved relevant improvements in sprint and COD and players in the MCT group increased SLJ and COD performance. The small effects on sprint and SLJ and the trivial in CMJ suggest that there was a reduced transfer between the intervention programs and the performance variables.

According to our results, OLT and MCT training programs may be prescribed during the competitive phase of the season to increase strength in basketball players without the use of heavy loads (> 85% 1RM) and without impairing the main physical performance variables (sprint, CMJ, SLJ and COD). The similar adaptations between OLT and MCT indicate that basketball sport scientists and strength and conditioning professionals may use either method to counteract possible strength losses during the season.

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Disclosure statement

The authors report no potential conflict of interest.

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