PUBLIC UNIVERSITY OF NAVARRE
DEPARTMENT OF HEALTH SCIENCES

Effect of plyometric training on explosive and endurance performance: influence of resting period, training volume and surface

Doctoral Thesis

Author: Rodrigo Ramírez Campillo

Supervisor : Dr. Mikel Izquierdo Redín

AGRADECIMIENTOS

Mis más sinceros agradecimientos al Dr. Mikel Izquierdo por ofrecerme la posibilidad de realizar esta Tesis Doctoral bajo su supervisión, y por supuesto, muchas gracias por haber dedicado parte importante de su tiempo a colaborar en las investigaciones que iniciamos a principios del 2011. Su apoyo y guía han sido claves en el proceso que hoy culmina en esta Tesis Doctoral. Todo lo que he aprendido en estos años bajo su guía han sido claves en mi proceso de formación como investigador.

También quiero agradecer de forma especial a todos los voluntarios (y a los apoderados de estos, en el caso de los trabajos realizados con menores de edad) que participaron en las investigaciones, ya que sin su colaboración y excelente disposición habría sido imposible la realización de esta Tesis Doctoral.

Por supuesto, agradezco a todos los colegas que participaron en las investigaciones, cuyo aporte fue fundamental para elaborar las propuestas de intervención, aplicar las intervenciones, analizar resultados, discutirlos y elaborar, revisar y traducir los manuscritos.

Muchas gracias al Departamento de Ciencias de la Actividad Física de la Universidad de Los Lagos, por haberme dado siempre la flexibilidad laboral necesaria para poder llevar a cabo mi actividad investigativa.

Muchas gracias a todas las personas que han sido una inspiración en mi vida profesional para querer seguir aportando evidencias a un campo laboral donde, lamentablemente, muchas actividades se desarrollan solo en base a creencias.

Muchas gracias a todos los deportistas que, con su esfuerzo, inspiran motivación para seguir elaborando propuestas que permitan ayudarles a mejorar su rendimiento y manifestar su máximo potencial.

Muchas gracias a todos.

LIST OF PUBLICATIONS

This doctoral thesis is a compendium of the following publications:

1. Ramírez-Campillo R, Álvarez C, Henríquez-Olguín C, Báez-San Martín E, Martínez C, Andrade DC, Izquierdo M (2013). Effects of plyometric training on endurance and explosive-strength performance in competitive middle and long distance runners. J Strength Cond Res DOI: 10.1519/JSC.0b013e3182a1f44c (Impact Factor: 1.831, Journal ranking: 2nd Quartile; Sports Sciences).

2. Ramírez-Campillo R, Andrade DC, Izquierdo, M. (2013). Effects of plyometric training volume and training surface on explosive strength. J Strength Cond Res. DOI: 10.1519/JSC.0b013e318280c9e9 (Impact Factor: 1.831, Journal ranking: 2nd Quartile; Sports Sciences).

3. Ramírez-Campillo R, Meylan C, Álvarez C, Henríquez-Olguín C, Martínez C, Cañas-Jamet R, Andrade DC, Izquierdo M (2013). Effects of in-season low volume-high intensity plyometric training on explosive actions and endurance of young soccer players. J Strength Cond Res. Epub ahead of print (Impact Factor: 1.831, Journal ranking: 2nd Quartile; Sports Sciences).

4. Ramírez-Campillo R, Meylan C, Álvarez-Lepín C, Henriquez-Olguín C, Martinez C, Andrade DC, Castro-Sepúlveda N, Burgos C, Baez EI, Izquierdo M (2013). The effects of interday rest on adaptation to 6-weeks of plyometric training in young soccer players. J Strength Cond Res. Epub ahead of print (Impact Factor: 1.831, Journal ranking: 2nd Quartile; Sports Sciences).

5. Ramírez-Campillo R, Andrade DC, Álvarez C, Henriquez-Olguín C, Martínez C, Báez EI, Silva-Urra J, Burgos C, Izquierdo M (2013). The effects of interset rest on adaptation to 7-weeks of explosive training in young soccer players. Submitted.

*Contribution of the PhD student: Literature search, study design, subjects' recruitment, data collection, statistical analysis, data interpretation and manuscripts preparation.

FUNDINGS

This Thesis has been done with the support of the following institutions:

- Universidad de Los Lagos, Department of Physical Activity Sciences, Osorno, Chile
- Laboratory of Sport Sciences Research, Universidad de Los Lagos, Osorno, Chile

SUMMARY

INTODUCTION: Endurance performance is a critical physiological component of performance in many long duration sports events. However, the ability to produce explosive strength with lower extremity muscles is a central issue in many sport activities as well. In fact, in some sports events of long duration, optimal explosive performance and neuromuscular characteristics related to voluntary and reflex neural activation, muscle force, running mechanics, and anaerobic characteristics may differentiate athletes of different performance level. Plyometric exercises are commonly used to increase explosive performance, with the advantage of requiring reduced physical space, time and equipment to complete the training sessions, hence integrating easily during regular training. High intensity drop jumps (DJ) are the most common exercises used during plyometric training (PT), including bounce drop jumps (BDJ). A BDJ involves a rapid coupling between an eccentric and concentric muscle action (i.e. stretch-shortening cycle - SSC). Training exercises based on a SSC are established techniques for enhancing athletic performance. This type of training may lead preferentially to adaptations such as increased rate of activation of motor units, with little or null impact on muscle hypertrophy, which may be an advantageous in sports of long duration. Therefore, this type of training appears as an interesting approach to improve athlete’s performance in sports where explosive performance and endurance are important for competition success, such as middle-long distance running and in youth soccer. However, due to the low number of scientific peer-reviewed manuscripts in these sports, and their methodological limitations, the impact of such training stimulus on the performance of athletes is not yet clear. In addition, although commonly accepted as an effective training method, previous studies have not established optimum PT design (i.e., volume, rest interval time between training sessions and training series) for performance enhancement. Also, the environment (i.e., landing surface) where PT took place had been poorly studied.

PURPOSE: To investigate the above mentioned issues, the present Thesis was composed by five studies with the following purposes: Study I: To determine the effects of PT, simultaneously applied with endurance running training, on a time trial running endurance performance test and explosive-strength adaptations in middle and long distance runners; Study II: To determine the effects of two different PT volumes (moderate vs. high), and training surfaces (hard vs. soft) on explosive performance characteristics of young recreationally soccer players; Study III: To determine the effect of replacing some soccer drills with low volume-high intensity vertical PT on explosive and endurance performance of young soccer players during in-season; Study IV: To determine how different rest intervals between sets of a PT program affects explosive strength, agility, running speed, and sport specific performance skills in young soccer players; Study V: To determine the effect of 24 and 48h of rest between PT sessions on explosive and endurance adaptations in young soccer players during in-season.

METHODS: In the study I, in order to examine the effect of a short-term PT program on explosive-strength and endurance performance in highly competitive middle and long distance runners, athletes were randomly assigned to a control group (CG, n=18, twelve men) and an explosive-strength training group (TG, n=18, ten men). The 20 (RSI20) and 40 (RSI40) cm drop jump reactive strength index, countermovement jump with arms (CMJA), 20-m sprint time (20-m), and 2.4 km endurance run time test were carried out before and after 6 weeks of explosive-strength training. Also, the combined standardized performance (CSP) in the endurance and explosive-strength test was analyzed. In the study II, to examine the effects of a previously

Universidad Pública de Navarra
Nafarroako Unibertsitate Publikoa

applied PT program (study I), but with different volume and training surfaces on explosive-strength performance, 29 subjects were randomly assigned to 4 groups: control group (CG, n = 5), moderate volume group (MVG, n = 9, 780 jumps), moderate volume hard surface group (MVG_{HS}, n = 8, 780 jumps), and high volume group (HVG, n = 7, 1,560 jumps). A series of tests were performed by the subjects before and after 7 weeks of PT. These tests were measurement of maximal strength (5 maximum repetitions [5RMs]), RSI20, RSI40, RSI60, squat jump (SJ), countermovement jump (CMJ), 20-m, agility, body mass, and height. In the study III, in order to investigate the effect of a short-term vertical PT program (the same program applied in study I and study II) within soccer practice to improve both explosive actions and endurance in young soccer players, 76 athletes were recruited and assigned either to a training (TG; n = 38; 13.2±1.8 y) or control (CG; n = 38; 13.2±1.8 y) group. All players trained twice per week for 90 minutes but the TG followed a 7-week PT implemented within soccer practice, while the CG followed regular soccer practice. The 20-m, Illinois agility test time, CMJ, RSI20, RSI40, multiple 5 bounds distance (MB5), kicking distance (MKD) and 2.4 km time trial test were applied prior and after the 7-week period. In the study IV, to determine the effect of different rest intervals between sets of a PT program (the same program applied in study I, study II, and study III) on explosive strength, agility, running speed, and sport specific performance skills in young soccer players, 61 athletes between 8-14 years of age were randomly assigned to 4 groups: control group (CG; n = 15), 30s rest interval group (G30; n = 13), 60s rest interval group (G60; n = 14) and 120s rest interval group (G120; n = 12). Participants trained 2 days a week for a total of 7 weeks. The RSI20, RSI40, CMJ, 20-m, L-run agility test time, and MKD test were performed before and after training. In the study V, to determine the effect of 24 and 48h of rest between PT sessions on explosive and endurance adaptations in young soccer players, 166 young male soccer players between 10 and 17 years of age were randomly divided into 3 training groups: control (C; n = 55), PT with 24h (PT24; n = 54) and 48h (PT48; n = 57) of rest between sessions. Players were recruited from 2 amateur soccer clubs with similar soccer-specific training load. Before and after intervention, players were measured in SJ, CMJ, RSI20, broad long jump (BLJ), 20-m, 10 x 5-m agility time test, 20-m multi-stage shuttle run test (MST) and sit and reach test (SR). The PT program was applied during 6 weeks, 2 sessions per week, with an initial load of 140 jumps per session, replacing some soccer-specific drills. All statistical analyses were performed with STATISTICA software (Version 8.0; Stat Soft, Inc, Tulsa).

RESULTS: The main findings after study I where that, after intervention, the CG did not showed any significant change in performance, while the TG showed a significant reduction in 2.4 km endurance run time (-3.9%) and 20-m sprint time (-2.3%) and an increase in CMJA (+8.9%), RSI20 (+12.7%), and RSI40 (16.7%) explosive-performance. The TG also exhibited a significant increase in CSP, while the CG showed significant reduction. The main findings after study II show that high training volume leads to a significant increase in explosive performance that requires fast SSC actions (i.e. RSI, sprint) in comparison to what is observed after a moderate training volume regimen. Second, when PT is performed on a hard training surface (high-impact reaction force), a moderate training volume induces optimal stimulus to increase explosive performance requiring fast SSC actions (e.g. RSI), maximal dynamic strength enhancement, and higher training efficiency. In the study III, the main findings were that PT induced significant ($P<0.05$) and small to moderate standardized effect (SE) improvement in the CMJ (4.3%; SE = 0.20), RSI20 (22%; SE = 0.57), RSI40 (16%; SE = 0.37), MB5 (4.1%; SE = 0.28), Illinois agility test time (-3.5%, SE = -0.26), MKD (14%; SE = 0.53), 2.4 km time trial (-1.9%; SE = -0.27) performances, but had a trivial and non-significant effect on 20-m (-0.4%; SE = -0.03). No significant improvements were found in the CG. The primary findings in the study IV was that after intervention the G30, G60 and G120 groups showed a significant improvement in jump, agility, and kicking performance, with no differences between treatments. In study V, the main findings was that after intervention, the CG did not show significant performance changes, however the PT24 and PT48 groups showed a small to moderate significant improvement in all performance tests ($p<0.001$), with no differences between treatments.

CONCLUSIONS: The conclusions of the present Doctoral Thesis were that: (I) properly programmed concurrent explosive strength and endurance training could be advantageous for middle- and long-distance runners in their competitive performance, especially in events characterized by sprinting actions with small time differences at the end of the race (study I); (II) after 7 weeks of PT, performance enhancement in maximal strength and in actions requiring fast SCC muscle activity (i.e. RSI, sprint) were dependent on the volume of training and the surface on which it was performed (study II); (III) an integrated vertical PT program within regular soccer practice can substitute soccer drills to improve most explosive actions and endurance, but horizontal exercises should also be included to enhance sprinting performance (study III); (IV) the use of 30, 60, or 120 s of rest between sets ensure significant and similar adaptations during high-intensity short-term explosive training in young male soccer players (study IV); (V) although it has been recommended that plyometric drills should not be conducted on consecutive days, the study shows that plyometric training applied twice weekly on consecutive or non-consecutive days result in similar explosive and endurance adaptations in young male soccer players (study V).

RESUMEN

INTODUCCIÓN: el rendimiento de resistencia cardiovascular es un componente fisiológico crítico en muchos eventos deportivos de larga duración. Sin embargo, la habilidad para producir fuerza explosiva con los músculos de las extremidades inferiores es también un tema central en muchas actividades deportivas. De hecho, en algunos eventos deportivos de larga duración, el rendimiento explosivo óptimo, las características neuromusculares relacionadas con activación neural refleja y voluntaria, la fuerza muscular, la mecánica de carrera, y las características anaeróbicas podrían permitir diferenciar a deportistas de diferente nivel de rendimiento. Los ejercicios pliométricos son comúnmente utilizados para incrementar el rendimiento explosivo, con la ventaja de requerir poco espacio físico, tiempo y equipamiento para completar las sesiones de entrenamiento, por lo que se integra fácilmente durante el entrenamiento regular. Los saltos con caída (DJ) de alta intensidad son los ejercicios más comúnmente utilizados durante entrenamiento pliométrico (PT), incluyendo saltos con caída y rebote (BDJ). Un BDJ implica un rápido acoplamiento entre una acción muscular excéntrica y una concéntrica (i.e. ciclo de estiramiento y acortamiento – SSC). Los ejercicios de entrenamiento basados en el SSC son técnicas establecidas para el mejoramiento del rendimiento deportivo. Este tipo de entrenamiento podría conducir, preferencialmente, hacia adaptaciones como el incremento del ritmo de activación de las unidades motoras, con poco o nulo impacto sobre la hipertrofia muscular, lo cual podría ser una ventaja en deportes de larga duración. Por tanto, este tipo de entrenamiento aparece como un interesante acercamiento para mejorar el rendimiento del deportista en disciplinas donde el rendimiento explosivo y de resistencia cardiovascular son importantes para el éxito competitivo, como en las carreras de medio fondo y fondo, y el futbol infantil-juvenil. Sin embargo, debido al bajo número de manuscritos científicos revisados por pares en estos deportes, y a sus limitaciones metodológicas, el impacto de este tipo de estímulo de entrenamiento sobre el rendimiento de los deportistas aun no es claro. Además, si bien comúnmente se acepta como un método de entrenamiento efectivo, estudios previos no han establecido diseños óptimos de PT (i.e. volumen, intervalo de descanso entre sesiones de entrenamiento y series de entrenamiento) para el incremento de rendimiento. Además, el ambiente (i.e. tipo de terreno) donde se lleva a cabo el PT ha sido pobremente estudiado.

PROPÓSITO: para investigar los temas antes mencionados, la presente Tesis se compuso de cinco estudios con los siguientes propósitos: Estudio I: Determinar los efectos del PT, aplicado simultáneamente con entrenamiento de fondo y medio fondo, sobre el rendimiento en una prueba de carrera contra el tiempo de 2.4 km y sobre adaptaciones de fuerza explosiva en corredores de medio fondo y fondo; Estudio II: Determinar los efectos de dos volúmenes diferentes de PT (moderado vs. alto), y de dos superficies de entrenamiento (dura vs. suave) sobre las características de rendimiento explosivo de jóvenes jugadores de fútbol recreativo. Estudio III: Determinar los efectos del remplazo de algunos ejercicios de fútbol con PT vertical de bajo volumen y alta intensidad, sobre el rendimiento explosivo y de resistencia cardiovascular de futbolistas jóvenes durante la temporada competitiva; Estudio IV: Determinar cómo diferentes intervalos de descanso entre series, durante un programa de PT, afectan la fuerza explosiva, agilidad, velocidad de carrera, y las habilidades de rendimiento deportivo específico de futbolistas jóvenes; Estudio V: Determinar los efectos de 24 y 48h de descanso entre sesiones de PT sobre las adaptaciones explosivas y de resistencia cardiovascular de jóvenes futbolistas durante la temporada competitiva.

MÉTODOS: En el estudio I, para examinar el efecto de un programa de PT de corta duración sobre la fuerza-explosiva y el rendimiento de resistencia cardiovascular en corredores de medio fondo y fondo altamente competitivos, los deportistas fueron distribuidos al azar en un grupo control (CG, n=18, 12 hombres) y en un grupo de entrenamiento de fuerza-explosiva (TG, n=18, 10 hombres). Antes y después de 6 semanas de entrenamiento de fuerza-explosiva se determinó el índice de fuerza reactiva para saltos con caída desde 20 (RSI20) y 40 (RSI40) cm, el salto con contra-movimiento con brazos (CMJA), el tiempo de sprint en 20-m (20-m), y el tiempo en una carrera de 2.4 km (2.4 km). Además, el rendimiento estandarizado combinado (CSP) en los test de 2.4 km y de fuerza-explosiva fue analizado. En el estudio II, para examinar los efectos de un programa de PT previamente aplicado (Estudio I), pero con diferente volumen y superficie de entrenamiento, sobre el rendimiento de fuerza-explosiva, 29 sujetos fueron asignados aleatoriamente a 4 grupos: grupo control (CG, n = 5), grupo volumen moderado (MVG, n = 9, 780 saltos), grupo volumen moderado y superficie dura (MVG_{HS}, n = 8, 780 saltos), y grupo volumen elevado (HVG, n = 7, 1,560 saltos). Una serie de test fueron realizados por los sujetos antes y después de 7 semanas de PT. Los test correspondieron a mediciones de fuerza máxima (5 repeticiones máximas [5RMs]), RSI20, RSI40, RSI60, salto desde cuclilla (SJ), salto con contra-movimiento (CMJ), 20-m, agilidad, masa corporal y talla. En el estudio III, para investigar el efecto de un programa de PT vertical de corta duración (el mismo programa aplicado en los estudios I y II) implementado dentro de las prácticas regulares de fútbol, sobre las acciones explosivas y de resistencia cardiovascular de jóvenes futbolistas, 76 deportistas fueron reclutados y asignados ya sea a un grupo de entrenamiento (TG; n = 38; 13.2±1.8 años de edad) o a un grupo control (CG; n = 38; 13.2±1.8 años de edad). Todos los jugadores entrenaban 2 veces por semana durante 90 min, pero el TG completó 7 semanas de PT (implementado dentro de las prácticas de fútbol), mientras que el CG completó únicamente sus prácticas regulares de fútbol. Antes y después del periodo de 7 semanas de intervención, los futbolistas completaron los test de 20-m, tiempo en el test de agilidad de Illinois, CMJ, RSI20, RSI40, distancia en el salto quíntuple (MB5), distancia de pateo (MKD) y 2.4 km. En el estudio IV, para determinar el efecto de diferentes intervalos de descanso entre series de un programa de PT (el mismo programa aplicado en los estudios I, II y III) sobre la fuerza-explosiva, la agilidad, la velocidad de carrera, y la habilidad de rendimiento deportiva-específica en jóvenes futbolistas, 61 deportistas entre 8 y 14 años de edad fueron distribuidos aleatoriamente en 4 grupos: grupo control (CG; n = 15) y grupos con 30 (G30; n = 13), 60 (G60; n = 14) y 120 (G120; n = 12) segundos de descanso entre series. Los participantes entrenaron 2 días a la semana durante 7 semanas. Antes y después de las 7 semanas se realizaron los test RSI20, RSI40, CMJ, 20-m, MKD y el test de carrera en L para agilidad. En el estudio V, para determinar el efecto de 24 y 48h de descanso entre sesiones de PT sobre las adaptaciones explosivas y de resistencia cardiovascular en jóvenes futbolistas, 166 jugadores de sexo masculino entre 10 y 17 años de edad fueron aleatoriamente divididos en 3 grupos: control (C; n = 55), PT con 24h (PT24; n = 54) y 48h (PT48; n = 57) de descanso entre sesiones. Los jugadores fueron reclutados desde 2 clubes de fútbol amateur con similar carga de entrenamiento específica de fútbol. Antes y después de la intervención los jugadores fueron evaluados en SJ, CMJ, RSI20, salto largo horizontal (BLJ), 20-m, tiempo en el test de agilidad de 10 x 5-m, tiempo en el test de carrera multi-etapas de ir y venir de 20-m (MST), y en el test de flexibilidad de sentar y alcanzar (SR). El programa de PT fue aplicado durante 6 semanas, 2 sesiones por semana, con una carga inicial de 140 saltos por sesión, remplazando algunos ejercicios específicos de fútbol. Todos los análisis estadísticos se realizaron con el software STATISTICA (Versión 8.0; Stat Soft, Inc, Tulsa).

RESULTADOS: Los principales hallazgos en el estudio I muestran que, luego de la intervención, el CG no mostró cambios significativos de rendimiento, mientras que el TG mostró una reducción significativa en el tiempo de carrera de 2.4 km (-3.9%) y 20-m (-2.3%), y un incremento en el rendimiento explosivo de CMJA (+8.9%), RSI20 (+12.7%), y RSI40 (16.7%). El TG también mostró un incremento significativo en el CSP, mientras que el CG mostró una reducción significativa. Los principales hallazgos en el estudio II muestran que un elevado volumen de entrenamiento conduce a un incremento significativo en el rendimiento explosivo dependiente de acciones de SSC rápidas (i.e. RSI, sprint) en comparación con lo observado luego de un PT de moderado volumen de entrenamiento. Además, cuando el PT se realiza sobre una superficie dura (fuerzas de reacción de alto impacto) un moderado volumen de entrenamiento induce un estímulo óptimo para incrementar el rendimiento explosivo dependiente de acciones SSC rápidas (e.g. RSI), la fuerza dinámica máxima, y una mayor eficiencia de entrenamiento. En el estudio III los principales hallazgos indican que el PT indujo un incremento significativo ($P<0.05$) y un efecto estandarizado (SE) pequeño a moderado en el rendimiento de CMJ (4.3%; SE = 0.20), RSI20 (22%; SE = 0.57), RSI40 (16%; SE = 0.37), MB5 (4.1%; SE = 0.28), tiempo en el test de agilidad de Illinois (-3.5%, SE = -0.26), MKD (14%; SE = 0.53) y test de 2.4 km (-1.9%; SE = -0.27), pero tuvo un efecto trivial y no significativo sobre el test de 20-m (-0.4%; SE = -0.03). No se observaron cambios significativos en el CG. En el estudio IV los principales hallazgos indican que tras la intervención los grupos G30, G60 y G120 mostraron un incremento significativo en saltabilidad, agilidad y rendimiento de pateo, sin diferencias entre grupos. En el estudio V los principales hallazgos muestran que tras la intervención el CG no cambió significativamente su rendimiento, mientras que los grupos PT24 y PT48 mostraron un incremento significativo pequeño a moderado en todos los test de rendimiento ($P<0.001$), sin diferencias entre tratamientos.

CONCLUSIONES: las conclusiones de la presente Tesis Doctoral indican que: (I) el entrenamiento concurrente bien programado de medio fondo y fondo junto con el de fuerza-explosiva podría ser ventajoso para el rendimiento competitivo de corredores de medio fondo y fondo, especialmente en eventos caracterizados por acciones de sprint con pequeñas diferencias de tiempo al final de una carrera (estudio I); (II) luego de 7 semanas de PT, el incremento de rendimiento de fuerza máxima y en acciones que requieren de actividad muscular dependiente de SSC rápidos (i.e. RSI, sprint) se ve influenciado por el volumen de entrenamiento y por la superficie en donde este se realiza (estudio II); (III) un programa de PT vertical integrado dentro de la práctica regular de fútbol puede sustituir algunos ejercicios específicos de futbol para mejorar la mayoría de las acciones explosivas y la resistencia cardiovascular, pero ejercicios pliométricos horizontales también deberían incluirse para mejorar el rendimiento de sprint (estudio III); (IV) el uso de 30, 60, o 120 s de descanso entre series pliométricas asegura adaptaciones significativas y similares durante el entrenamiento explosivo de alta intensidad a corto plazo en jóvenes futbolistas de sexo masculino; (V) aunque se ha recomendado que los ejercicios pliométricos no se efectúen en días consecutivos, el estudio mostró que el PT aplicado dos veces a la semana en días consecutivos o alternados, resulta en similares adaptaciones de rendimiento explosivo y resistencia cardiovascular en jóvenes futbolistas de sexo masculino (estudio V).

CONTENTS

LIST OF FIGURES AND TABLES

LIST OF ABBREVIATIONS

%	Percentage
20-m	Twenty meters sprint time test
5RM	Five repetitions maximum (maximal strength)
BDJ	Bounce drop jump
BLJ	Broad long jump test
BMI	Body mass index
CG	Control group
CL	Confidence limits
CMJ	Countermovement jump test
CMJA	Countermovement jump with arms test
CSP	Combined standardized performance
ES	Effect size
G30	30s rest interval group
G60	60s rest interval group
G120	120s rest interval group
HVG	High volume group
ICC	Reliability coefficients
MB5	Multiple 5 bounds test
MKD	Maximal kicking distance test
MST	20-m multiple-stage shuttle run test
MVG	Moderate volume group
MVG_{HS}	Moderate volume hard surface group
PT	Plyometric training

PT24	Plyometric training with 24 hours of rest between sessions
PT48	Plyometric training with 48 hours of rest between sessions
RM	Repetitions maximum
RSI20	Twenty cm drop jump reactive strength index
RSI40	Forty cm drop jump reactive strength index
RSI60	Sixty cm drop jump reactive strength index
SD	Standard deviation
SE	Standardized effect
SJ	Squat jump test
SSC	Stretch-shortening cycle
SR	Sit and reach test
TG	Training group

1. INTRODUCTION

Plyometric training (PT) is a strength training method commonly used to increase explosive performance, with the advantage of requiring reduced physical space, time and equipment to complete the training sessions, hence integrating easily during regular training. High intensity drop jumps (DJ) are the most common exercises used during plyometric training, including bounce drop jumps (BDJ). A BDJ involves a sudden eccentric muscle action, which activates a reflex contraction and higher muscle activity, as well as involves a rapid coupling between an eccentric and concentric muscle action (i.e. stretch-shortening cycle - SSC) (10). Training exercises based on a SSC are established techniques for enhancing athletic performance. This type of training may lead preferentially to adaptations such as increased rate of activation of motor units (49-50), with little or null impact on muscle hypertrophy, which may be important in sports where endurance and/or muscle power relative to body weight is relevant to performance. However, although commonly accepted as an effective training method, previous studies have not established optimum PT variables design (e.g., volume, rest interval time between training sessions and training series, frequency, type of landing surface) for performance enhancement.

1.1. Plyometric training: its effect on endurance performance ability

Endurance performance ability depends on several factors, like VO2max, lactate threshold and running economy (20). In addition, may also require optimal neuromuscular characteristics related to voluntary and reflex neural activation, muscle force and elasticity, running mechanics, and anaerobic characteristics (50, 106, 130). In fact, some studies (18, 60) have shown that anaerobic characteristics can differentiate well-trained endurance athletes according to their performance. Recently, it has been reported that when proper strength training is used simultaneously with endurance training, improvements in strength and endurance performance is possible in world-class endurance athletes (41-42). On the other side, concurrent strength and endurance training have proved detrimental to endurance performance (77).

While a traditional heavy-resistance training program results mainly in neural and hypertrophic adaptations (50, 52) and leads to a dilution of the mitochondrial volume density (83), explosive-strength training may lead preferentially to adaptations such as increased rate of activation of motor units (50, 52). Therefore, PT (a type of explosive-training) appears as an interesting training method for endurance performance. In fact, short-term PT may have a positive effect on endurance, (150) although the scarce literature and their limitations preclude final conclusions regarding the effects of PT on this ability.

1.2. Plyometric training in recreational youth soccer players: effect of the volume and surface

The volume and type of training surface during plyometric workout may affect the type of SSC being performed (fast vs. slow), implying different biomechanical and physiological effects (10), and possible different long-term adaptations. Therefore, it may be suggested that depending on the type of SSC stimulus, one may devise different PT adaptations. However, to the best of the authors' knowledge, a limited amount of scientific literature has controlled these determinant variables (62, 133).

Regarding training volume, it is notorious the important differences in volume used among studies reported in the literature. In this line, significant and positive changes in performance had been show with PT volumes of 8 to 40 jumps per session (91), 16 to 32 jumps per session (43), 18 to 60 jumps per session (146), 39 jumps per session (112), 60 to 100 jumps per session (67), 72 jumps per session (58), 90 to 105 jumps per session (56), 102 to 240 jumps per session (113), 100 to 672 jumps per session (75), 270 to 640 jumps per session (24), and 300 to 1000 jumps per session (119). Therefore, several studies show that different volumes of high intensity drop jump-based PT can induce performance enhancement; however, there are very little scientific evidence comparing the effect of different volumes of drop jump-based PT on performance. To the best of the author knowledge, only one study analyzed the effect of low, moderate and high volume of high intensity drop jump-based PT. In this study a low and a moderate volume of PT produced greater explosive gains compared with high volume PT (27). Similar results have been found in weight-lifting training studies (44-45) regarding the higher efficiency of moderate volume-high intensity training compared to higher volumes of training.

Regarding PT environment (i.e. training surface), Stemm and Jacobson (133) trained a group of athletes with the same plyometric program but with different training surfaces (water vs. sports mat). Both groups improved performance, but no differences between regimens were observed. In another study, Impellizzeri et al. (62) examined the effect of 4 weeks of PT in a soccer team that trained on grass vs. sand surfaces. Both groups obtained similar improvements in squat jump (SJ), but the grass training group obtained a significant increase in CMJ and SJ÷CMJ reactive index vs. the sand trained group. On the other hand, the sand trained group experienced less muscle pain. Unfortunately, none of these studies quantified the hardness of the training surfaces with their respective restitution coefficient. This is determined by the separation velocity and the approximation velocity of two objects before and after they collide and is expressed in absolute values (92).

Thus, further research is needed to clarify the effect of PT factors such as volume and training surface on performance adaptations.

1.3. Plyometric training in youth soccer players: its effect on endurance and explosive performance ability

In some long-time duration sports, endurance ability is an important physical component of successful performance. However, the ability to produce high explosive muscle actions during short duration competitive actions may be critical to decide situations of victory or defeat. One of such sport is soccer, where the capacity to produce varied powerful actions during a 90-minute game is associated with high aerobic capacity (134). Indeed, the ability to produce an explosive single-bout effort is an important training factor determinant for success in soccer (5, 33). This includes movements such as sprinting, jumping, changing direction, throwing or kicking frequently occurring in soccer (134). Many of these activities not only require maximal power but also a high rate of power development considering the short period spent on the ground to produce power, such as sprinting or changing direction (< 100 ms) (15, 93). Various studies demonstrated that youth elite and/or sub-elite players were found to be faster, more agile and more powerful than non-elite (53, 140), while, future international and professional players had superior explosive characteristics (i.e. speed, power) at youth level than future amateur players (72). These results support the fact that soccer-related, explosive activities requiring power may not only be important qualities at youth level (53, 140) but also at a later stage of a player's career (72) and need to be developed from a young age.

Plyometric exercises are commonly used to increase explosive actions in pubertal (135) and prepubertal (28, 95-96) soccer players, with the advantage of being easy to integrate in soccer practice (space, time, equipment), and replicate the neuromuscular stimulus encountered in explosive soccer activities such as sprinting and jumping (43). Previous studies demonstrated that high intensity plyometric exercises (i.e. drop jumps) can be used safely and effectively, from the beginning of training, in young boys (19) and soccer players (135), and even had been advocated as a preventive injury strategy (35, 76) or as a rehabilitation tool (55). Generally, the high intensity requirements of drop jump training imply a reduced volume in training (19, 27) and therefore may require less time to complete than other plyometric modes, while inducing comparable training adaptations (135). The ability to continue improving explosive action during in-season is a challenge due to the limited time available for isolated training when the emphasis is mostly placed on technical development in youth soccer (94). It has been demonstrated (95) that in-season high volume PT (~100-120 ground contact per session) can increase explosive performance, but it remains unknown whether a low volume high intensity training may induce similar changes in sprinting, jumping and change of direction. Such approach may appear relevant to the time constraint that coaches may encounter for both physical and technical development of players.

Apart from sprinting, jumping and change of direction, explosive training may also be beneficial to other soccer specific athletic requirements such as ball kicking or endurance. Previous studies (96, 149) investigating kicking performance demonstrated the efficiency of explosive training to improve this quality, but improvement in aerobic performance remained controversial. Some studies in explosive training in youth soccer players did not demonstrate any improvement in VO2max (96) or lactate thresholds (46), while others (149) demonstrated the efficiency of explosive training to improve Yo-Yo intermittent recovery test performance and sub maximal running cost, likely associated with improvement in anaerobic and/or neuromuscular capabilities (89). Similarly, research in adult runners demonstrated that PT may improve running time trial and economy but not VO2max and lactate threshold (108, 131, 138). It is therefore of interest to identify if PT in youth players have a positive influence on middle distance running time trial, considering its multiple facet requirement (VO2max, lactate threshold and running economy) (108), likely to affect aerobic performance in soccer (134).

1.4. Plyometric training in youth soccer players: effect of the rest period between sets

Although the primary governing factors regulating the performance of repeated power-oriented drills are their intensity, duration and recovery duration (4), the characteristics of between sets recovery of a PT that generates optimal gains are not clear (123), especially in young soccer players. To the best of the authors' knowledge a limited number of studies have established the optimum PT design (i.e. interset rest intervals) for explosive strength enhancement (26). Rest interval can have a significant acute effect on metabolic, hormonal, cardiovascular, and performance responses to strength exercise (40, 69, 71). Therefore, adequate rest may be vital to ensure the quality of each repetition being performed in exercise sets designed to develop muscle power (4). Two to five min of rest had been recommended between sets when training for muscle power (4), or even 10 min between sets of high intensity BDJ (12). However, only a few longitudinal studies suggest that different resting intervals between sets will significantly affect gains in muscle performance (26). Thus, although statements regarding rest interval between power-PT sets have been made, the scientific evidence to sustain these recommendations is limited, especially in young soccer players were the research is scarce.

In adult soccer players a recovery period of 25-30 s was adequate to maintain plyometric performance during repeated 15-m sprints (3), and a 10 s recovery period was adequate to induce significant increases in sprint performance after 8 weeks of sprint training (124). In youths, the recovery capacity from high intensity plyometric exercises has been reported to be higher than in adults (86). A higher level of flexibility, slower muscle fiber-type composition, and a high level of habitual physical activity in youths may help explain their higher recovery ability after high intensity PT (86). Therefore, as young athletes recover from physical exertion can be faster than adults, especially from high-intensity exercise (32), one may hypothesize that brief (i.e. 30 s) interset rest intervals between PT drills could be viewed as an adequate recovery period to induce training adaptations in this population, especially when the duration of jump drills are taken into account (i.e. <1 s) (7, 22). Thus, it is needed to be addressed the question of how different interset rest intervals of a PT program may affect explosive strength, running speed, agility, and sport specific performance skills in young soccer players.

1.5. Plyometric training in youth soccer players: effect of the rest period between sessions

PT frequency (10, 87, 122-123, 127, 139) or the rest interval between training sessions (81, 89) may affect its outcome. In young soccer players, PT frequencies of 1 (84, 137), 2 (46, 68, 84, 95-96, 128, 135, 149) and 3 (28) sessions per week have been applied effectively. Curiously, most studies in which explosive strength training was applied to this group of athletes did not report the rest interval used between training sessions (28, 46, 68, 84, 135, 149). It has been recommended that plyometric drills should not be conducted in consecutive days in youths (30, 141). In addition, several interventions in young soccer players used >72 h (96, 128) or >48 h (95) of rest between plyometric training sessions *to allow for adequate recovery*, suggesting that these time frames of rest would be necessary to induce adequate training stimulation in this population of young athletes. However, to the best of the author knowledge, no studies have evaluated the effect of the rest interval between PT sessions in explosive and endurance performance of young soccer players.

In adults, improved performance had been reported with PT frequencies of 4-5 sessions per week (27, 38, 56, 123, 132), suggesting that less than 24 h of recovery between sessions may induce significant adaptations. In youths, the recovery capacity from high intensity plyometric exercises has been reported to be higher than in adults, and less than 24 h may be sufficient to recover from a previous explosive exercise stimulus (86). A higher level of flexibility (leading to less overextension of sarcomeres during eccentric exercise), slower muscle fiber-type composition, and a high level of habitual physical activity in youths may help explain their higher recovery ability after high intensity PT (86). Therefore, as young athletes recover from physical exertion can be faster than adults, especially from high-intensity exercise (32, 86, 115-116), one may hypothesize that 24 h of rest between PT sessions could be viewed as an adequate recovery period to induce training adaptations in this population. Considering that some young soccer teams schedule training sessions on consecutive days, it would be of practical and scientific interest to determine if two PT sessions per week, with 24 or 48 h of rest between them, would result in significant differences in explosive strength and endurance adaptations between the two recovery windows, as well as with no additional explosive training in young soccer players.

Given the relevance of endurance and explosive performance to the competitive capacity of athletes, together to the few data regarding the effect of acute PT variables manipulation (i.e. rest between sets, rest between sessions, volume, surface), on these abilities in young soccer players, the present doctoral thesis is composed of five separate studies (I-V). Therefore, the hypotheses are as follows:

2. HYPOTHESES

H_1. In distance runners, PT would increase endurance and explosive performance (Study I).

H_2. In recreationally young soccer players, enhancement of explosive performance after PT would be dependent on the volume of training and the surface on which it was performed (Study II).

H_3. In young soccer players, replacement of some soccer drills with low volume-high intensity PT would increase endurance and explosive performance (Study III).

H_4. In young soccer players, enhancement of explosive performance during a short-term PT program would be similar with rest intervals of 30, 60 or 120 s between sets (Study IV).

H_5. In young soccer players, twenty-four hours of rest between PT sessions would be adequate to improve endurance and explosive performance (Study V).

To test the above mentioned hypotheses, five experiments were conducted with the following objectives:

3. OBJECTIVES

O_1. To determine the effects of PT, simultaneously applied with endurance running training, on a time trial running endurance performance test and explosive-strength adaptations in middle and long distance runners (Study I).

O_2. To determine the effects of two different PT volumes (moderate vs. high), and training surfaces (hard vs. soft) on explosive strength performance characteristics of recreationally young soccer players (Study II).

O_3. To determine the effect of replacing some soccer drills with low volume-high intensity vertical PT on explosive actions and middle distance time trial performance of young soccer players during in-season (Study III).

O_4. To determine how interset rest intervals of 30, 60 and 120 s during a short-term PT program affects explosive strength, agility, running speed, and sport specific performance skills in young soccer players (Study IV).

O_5. To determine the effect of 24 and 48h of rest between PT sessions on explosive and endurance adaptations in young soccer players during in-season (Study V).

4. METHODS

4.1. Study I

4.1.1. Experimental Approach to the Problem

It was examined the ability of a short-term PT program to improve explosive-strength and running endurance performance. To do this, it was compared the effects of 6 weeks of PT in two groups of athletes, formed from competitive middle and long distance runners; one group added plyometric drills to their regular running endurance training (TG), and the other followed only the regular running endurance training (CG). Some initial tests were executed to establish a baseline. Tests were related to different jump variables, acceleration, endurance, and anthropometrics. This was a randomized controlled trial. The assigned groups were determined by a chance process and could not be predicted.

4.1.2. Subjects

From the initial sample of 53 middle and long distance runners, who volunteered to take part in this study and had the necessary requirements to integrate the study, and following a random distribution of the athletes in the investigation groups, only 36 applied as their initiative (22.1 ± 2.7 years of age; CG, n = 18, twelve men; TG, n = 18, ten men). They had a minimum of two years of competitive experience at national and international level, with personal best times that ranged from 3:50 and 4:27 min:s at the 1500m (men and women, respectively) to 2:32 and 2:52 h:min at the Marathon (men and women, respectively). Subjects had no explosive-strength training experience in the last 6 months. Athletes completed (mean ± standard deviation) 6.94 ± 1.8 running endurance training units per week, for a total running weekly volume of 67.2 ± 18.9 km (TG 64.7 ± 18.8 km; CG 70.0 ± 19.3 km; no significant difference between groups), where high intensity interval training bouts of long (i.e. >1 min) duration were the preferred training method. This training load was added to their respective competitive schedule. Although the VO_2max was not measured, the whole group of athletes (including women) underwent a 2.4 km time trial running performance test in a mean of 7.9 ± 0.8 min before intervention, suggesting a high level of fitness in comparison with previous reports (108, 126, 130-131). Exclusion criteria included athletes with: 1) potential medical problems or a history of ankle, knee, or back pathology in the 3 months preceding the study, 2) medical or orthopedic problems that compromised their participation or performance in this study, 3) any lower extremity reconstructive surgery in the past 2 years or unresolved musculoskeletal disorders, and 4) athletes who were taking and had previously taken anabolic steroids, growth hormone, or related performance-enhancement drugs of any kind. However, individuals were not eliminated if they had been taking vitamins, minerals, or related natural supplements (other than creatine monohydrate). Institutional Review Board approval for the study was obtained, and all athletes were carefully informed about the experiment procedures, and about the possible risks and benefits associated with participating in the study, and an appropriate signed informed consent document was obtained pursuant to law before any of the tests were performed. The study complies with the World Association's Declaration of Helsinki. Sample size was computed according to changes observed in plyometric (i.e. jumping) performance (δ = 3.2%; SD = 0.9) in a group of endurance runners submitted to training for 6 weeks (108). A total of 15 participants per group would yield a power of 80% and α of 0.05. The rate of runners who completed the PT program was 89%. From the 36 athletes that initially took part in the study, one male from the TG and three (1 female and 2 male) from the CG did not complete the post intervention measurements due to several reasons: injury (non PT related), change of residency, and pregnancy. No injuries related to the PT program were reported.

4.1.3. Testing Procedures

All anthropometric measurements were completed between 10:00–11:00 h, whereas performance measurements were completed between 11:00 and 16:00 h. Height was measured using a wall-mounted stadiometer (Butterfly, Shanghai, China) recorded to the nearest 0.5 cm. Body mass was measured to the nearest 0.1 kg using a digital scale (BC-554 Ironman Body Composition Monitor, Tanita, Illinois, USA). The body mass index (BMI) was determined by dividing body mass by the square height of the athlete ($kg \cdot m^{-2}$). The athletes were carefully familiarized with the test procedures during several sub maximal and maximal actions a few days before the measurements were taken (2 sessions per week during 2 weeks). The athletes also completed several explosive type actions to become familiar with the exercises used during training. In addition, several warm-up muscle actions were performed prior to the actual maximal and explosive test actions. All tests were carried out before and after 6 weeks of PT. The performance tests were performed in two non-consecutive days. On day 1, the following tests were completed: measurement of height (m), body mass (kg), CMJA (cm), RSI20 and RSI40 ($cm \cdot ms^{-1}$). On day 2, the 20-m, and 2.4 km running endurance test were completed. Standard warm-up (5 minutes of sub maximal running with several displacements, and 2 sub maximal jump exercises of 20 vertical jumps and 10 longitudinal jumps) were executed during each testing day. Also, athletes were instructed to use the same sports clothing during the pre and post intervention testing, to have a good night of sleep before each testing day, to avoid drinking or eating at least 2–3 h before measurements. All subjects were motivated to give their maximum effort during performance measurements and all performance test were executed at least 48h after a hard training session.

Bounce Drop Jump. The athletes performed BDJs from a 20, and 40-cm high platform for maximum jump height and minimum contact time, in order to assess plyometric performance requiring fast SSC action. The objective was to maximize the ratio between height and ground contact time ($cm \cdot ms^{-1}$), using an electronic contact mat system (Globus Tester, Codogne, Italy). A protocol previously described (19) was used to test athletes. The ICC was 0.93 (0.91-0.95) for 20-cm BDJ and 0.92 (0.90-0.94) for 40-cm BDJ.

Countermovement Jump With Arms. A CMJA was used in order to assess plyometric (i.e. maximal jump height; cm) performance requiring slow SSC action and the coordination between lower and upper body muscles. The CMJA test was performed using an electronic contact mat system (Globus Tester, Codogne, Italy). Jump height was determined using an acknowledged flight-time calculation (13, 27). During de CMJA, the athlete was instructed to use arms freely, foot and shoulders wide apart; athletes performed a downward movement with no restriction on the knee angle achieved (131), followed by a maximal effort vertical jump. All athletes were instructed to land in an upright position and to bend their knees following landing. Three trials were completed, with 30 s of rest between them, and the best performance trial was used for the subsequent statistical analysis. The ICC was 0.92 (0.89-0.95) for CMJA measurements.

20-m Sprint Time. Sprint times (s) were recorded for 20-m distances in order to assess horizontal explosive-strength performance requiring fast SSC action during running, a measure previously used to asses plyometric performance in endurance runners (108). A protocol previously described (19) was used to test athletes. Briefly, the 20-m sprint test was conducted indoors on a wooden running surface. The sprint time was measured to the nearest 0.01 s using infrared reds photoelectric cells (Globus Italia, Codogne, Italy) positioned at 20 m. Three trials were completed, and the best performance trial was used for the subsequent statistical analysis. Three minutes of rest were permitted between 20-m trials. The ICC was 0.95 (0.94-0.98) for 20-m sprints measurements.

2.4 km Running Endurance Test. This was the only test that took place outdoors. The wind velocity at all times was between 5.5 to 9.9 km·h^{-1}, the relative humidity was 50-66% and the temperature was 13-14°C (Chilean Meteorological Service, Santiago, Chile). Athletes were instructed to run for maximal performance. The head coach took results as a guide to select athletes for competition, so motivation was considered maximal. Athletes individually completed 6 laps in a 400-m outdoor polyurethane track. Because the middle and long distance runners recruited for the study compete in different distances, it was choose a standard distance for all athletes (2.4 km), as all of them were accustomed to this test as part of their annual general fitness assessment battery. For the specific warm up, two sub maximal laps around the track were completed, and 4 min later athletes had one maximal attempt to complete the test.

Combined Standardized Performance. The combined standardized performance (CSP) was analyzed. To obtain CSP, dependent performance variables were standardized by means of the Z score equation: z = (r – X) ÷ SD, were r is the raw score (e.g. 33 cm in the CMJA), X is the population mean, and SD is the population standard deviation (SD). The performance variables standardized were 20m, 2.4km, CMJA, RSI20, and RSI40. The mean of each standardized performance variable was obtained, then combined, and finally divided by the total number of performance variables standardized. Where a smaller number represents a better result (such as running performance), the standardized value (i.e. -0.8) was reversed (0.8 in the example), and thus a positive value represent a positive performance regarding the total group of athletes. The higher the value, the better was the athlete's performance within the group of 36 individuals that took part in the study.

4.1.4. Plyometric Training Program

The PT intervention period lasted for 6 wk, as this time frame had shown to be adequate for significant endurance related adaptations (108, 131, 138), and was carried out during the initial part of the competition season. No reduction in running endurance training volume was applied to the TG (i.e. the TG and CG kept their usual volume of running endurance training during the intervention). The athletes were instructed to maintain their usual dietary habits for the entire duration of the study and they did not perform plyometric exercise during intervention (other than the planned explosive-exercises for the TG). Before the initiation of the PT period, the athletes were instructed as to the proper execution of all the exercises to be done during this period. The PT took place 2 days per week (with at least 48 hours of rest between sessions), because this training frequency had been shown to induce significant explosive and endurance related adaptations in endurance athletes (131), with significant superior efficiency as compared with higher training frequencies (27). PT sessions lasted less than 30 min and were completed immediately before the endurance training. Standard warm-up (i.e. 5 minutes of sub maximal running and several displacements, 20 sub maximal vertical jumps and 10 sub maximal longitudinal jumps) was used prior to the main part of the training session. The plyometric exercises consisted only of BDJ, with a total of 60 BDJ per session (2 series of 10 jumps from a 20 cm box, 2 series of 10 jumps from a 40 cm box, and 2 series of jumps from a 60 cm box) for the TG. This volume has been used in previous studies, obtaining significant positive results (19, 27). The rest period between repetitions was of 15 s, as previously recommended (117), and between series was of 2 min. The CG did not perform PT and underwent the same testing protocols as the TG. Athletes from the TG used the same surface (i.e. wooden floor) to complete all the PT sessions. Athletes were instructed to place their hands on their hips and step off the platform with the leading leg straight to avoid any initial upward propulsion, ensuring a drop height of 20, 40, and 60 cm. They were instructed to jump with maximal intensity for maximal height and minimum contact time in every jump. These instructions were intended to maximize explosive-strength requiring fast SSC. A researcher was always present during training sessions, motivating athletes to give their maximum effort in each jump.

4.1.5. Statistical Analyses

Statistical analyses were performed by STATISTICA software (version 8.0, Stat Soft, Inc, Tulsa, Oklahoma, USA). Descriptive statistics (mean ± SD) for the different variables were calculated. Normality and homoscedasticity assumptions for all data (pre and post) were checked respectively with Shapiro-Wilk and Levene Tests. To determine the effect of intervention on plyometric and running endurance adaptations, a 2-way variance analysis with repeated measurements (2 groups × 2 times) was applied. When a significant F value was achieved across time or between groups, Tukey post hoc procedures were performed to locate the pairwise differences between the means. Pearson r product-moment correlation was used to correlate the initial value of the dependent variables and their relative modification after the intervention. The α level used for all statistics was 0.05.

4.2. Study II

4.2.1. Experimental Approach to the Problem

It was examined the ability of a short-term PT program using moderate or high volume, and hard or soft surface, to improve explosive physical performance. To do this, it was compared the effects of 7 weeks of PT in 4 groups of subjects, formed from young male recreationally soccer players; one group did not train and thus serve as a control (CG); a second group followed a moderate volume PT program (MVG); a third group followed a moderate volume hard surface PT program (MVG_{HS}); and a fourth group followed a high volume PT program (HVG). Some initial tests were executed to establish a baseline. Tests were related to different jump variables, maximal strength, acceleration, agility, and anthropometrics. This was a randomized controlled trial. The assigned groups were determined by a chance process and could not be predicted.

The initial tests were completed in 4 days (Monday, Tuesday, Thursday, and Friday). After the initial measurements, subjects were randomly assigned to their respective groups: CG (n = 5), MVG (n = 9, 60 jumps per session, for a total of 780 jumps), MVG_{HS} (n = 8, 60 jumps per session, for a total of 780 jumps), and HVG (n = 7, 120 jumps per session, for a total of 1,560 jumps). The study design (4 groups) allowed the comparison between HVG, MVG (both trained over soft surface), and a control group, to determine the effect of the independent variable volume, related to the first of our research questions. On the other hand, the comparison between MVG and MVG_{HS} (similar training volumes but on different coefficient restitution surfaces), as well as a control group, let us to determine the effect of the independent variable surface, related to the second of our research questions. Unfortunately, a fifth research group (high volume and hard surface) was not incorporated because of the high volume of PT, over hard training surface, may have increased the injury risk on the subjects (27). Thus, ethical issues preclude us to incorporate a fifth group. The training groups used the same intensity during exercises. Before beginning the training period, the subjects were instructed to properly execute all the exercises to be done during this period. The training protocol included BDJ from 3 different heights (20, 40, and 60 cm). All training sessions were supervised. The subjects were instructed to maintain their dietary habits for the whole duration of the study. Also, subjects were instructed to use the same sport shoes during the pre- and post intervention testing. Subjects from the MVG_{HS} used a hard (gymnasium floor) surface, whereas subjects from the HVG and MVG used a soft (athletic mat over gymnasium floor) surface to complete the PT. The hardness of the training surfaces was quantified by means of a restitution coefficient. The coefficient of restitution was determined by using a high-speed (300 frames per second) camera (Samsung, model sc-mx20c HD). This coefficient is commonly used to determine some physical characteristics for sports balls and other sports elements (i.e., baseball bat) (1). In the investigation, the restitution coefficient of a tennis ball (0.73) was used as a baseline to assess the impact of this type of ball on the athletic mat and gymnasium floor. The differences observed in the restitution coefficient where attributed to the surface characteristics of the mat and gymnasium floor (92). The athletic mat had a restitution coefficient of 0.53, and the gymnasium floor had a restitution coefficient of 0.8.

4.2.2. Subjects

This study involved a group of high school adolescent males (16.9 ± 0.9 years of age), that play recreationally soccer. None of the subjects had any background in regular strength training or competitive sports that involved any of the training methods used in the investigation. Because plyometric exercises may induce important adaptations, requiring reduced physical space, time, and equipment, they are commonly used during physical education classes and during initial phases of children's training and playing approaches.

Subjects were reminded during each training session to maintain their usual physical activity habits during the experiment. Exclusion criteria included subjects with (a) potential medical problems or a history of ankle, knee, or back pathology in the 3 months before the study, (b) medical or orthopedic problems that compromised their participation or performance in the study, (c) any lower extremity reconstructive surgery in the past 2 years or unresolved musculoskeletal disorders, and (d) subjects who were taking or had previously taken anabolic steroids, growth hormone, or related performance-enhancement drugs of any kind. However, individuals were not eliminated if they had been taking vitamins, minerals, or related natural supplements (other than creatine monohydrate). Institutional Review Board approval for our study was obtained, and all subjects (and their parents or guardians) were carefully informed about the experiment procedures and about the possible risk and benefits associated with participation in the study, and an appropriate signed informed consent document has been obtained pursuant to law before any of the tests were performed. The study complies with the human and animal experimentation policy statement guidelines of the American College of Sports Medicine.

4.2.3. Testing Procedures

All anthropometric measurements were completed between 10:00–11:00 h, whereas performance measurements were completed between 11:00 and 16:00 h. All subjects were instructed to have a good night of sleep before each testing day. Subjects were instructed to avoid drinking or eating at least 2–3 h before measurements. All subjects were motivated to give their maximum effort during performance measurements.

Height was measured using a wall-mounted stadiometer (Butterfly, Shanghai, China) recorded to the nearest 0.5 cm. Body mass was measured to the nearest 0.1 kg using a digital scale (BC-554 Ironman Body Composition Monitor, Tanita, IL, USA). The body mass index (BMI) was determined by dividing body mass by the square height of the subject (kilograms per square meters). The subjects were carefully familiarized with the test procedures during several sub maximal and maximal actions a few days before the performance measurements were taken (4 learning sessions during 2 weeks). The subjects also completed several explosive type actions to become familiar with the exercises used during training. In addition, several warm-up muscle actions were performed before the actual maximal and explosive test actions. All tests were carried out before and after 7 weeks of PT. The study was completed during winter. The performance tests were completed in 4 days. On day 1, the following tests were completed: height, body mass, SJ, and CMJ for maximal vertical distance (centimeters), RSI20, RSI40, and RSI60 ($cm \cdot ms^{-1}$). On day 2, the 20-m test was carried out; on day 3, the 5RM test was completed, and on day 4, the Illinois agility test (99) was completed. Ten minutes of standard warm-up (5 minutes of sub maximal running with several displacements, stretching exercises for 5 minutes, and 2 sub maximal jump exercises of 20 vertical jumps and 10 longitudinal jumps) were executed before each testing day.

Maximal Dynamic Strength (5 RM). A parallel squat test was selected to provide data on maximal dynamic strength of the lower extremity muscles. Maximal strength was assessed using concentric-eccentric 5RM parallel squat action. Parallel squat tests were completed using free weights, with the subject assuming an initial erect position with the bar behind the shoulders. Then, the subjects lowered the bar until the upper portion of the thighs was parallel with the floor (determined visually by the investigators). Finally, the subject performed a concentric leg extension (as fast as possible) to reach the full extension of 180 degrees against the resistance determined by the weight. This action was repeated 5 times, with the maximum weight possible. Warm-up consisted of a set of 10 repetitions at loads of 40–60% of the perceived maximum. After 1 minute of rest and mild stretching, subjects performed a second set of 3–5 repetitions at loads of 60–80% of the perceived maximum. Thereafter, the subjects had a maximum of 5 separate attempts to find their 5RM. The last acceptable 5 consecutive repetitions with highest possible load (kg) were determined as 5RM. The rest period between the actions was always between 3 and 5 minutes.

Explosive Strength. The subjects performed BDJ from a 20-, 40-, and 60-cm high platform, using an electronic contact mat system (Globus Tester, Codogne, Italy) with a precision of 0.01 m. The subjects were instructed to place their hands on their hips and step off the platform with the leading leg straight to avoid any initial upward propulsion ensuring a drop height of 20, 40, and 60 cm. They were instructed to jump for maximal height and minimal contact time, to maximize jump reactive strength. The subjects were again instructed to leave the platform with knees and ankles fully extended and to land in a similarly extended position to ensure the validity of the test. Four basic techniques were stressed: (a) correct posture (i.e., spine erect and shoulders back) and body alignment (e.g., chest over knees) throughout the jump; (b) jumping straight up with no excessive side-to side or forward-backward movement; (c) soft landing including toe-to-toe heel rocking and bent knees; and (d) instant recoil for the concentric part of the jump. Phrases such as “on your toes,” “straight as a stick,” “light as a feather,” and “recoil like a spring” were used as verbal and visualization cues during the BDJ. The instruction given to the subjects were “jump as high as you can, with minimum ground contact time.” Three repetitions were executed from each height, with 10–15 seconds between repetitions. The best performance trial was used for the subsequent statistical analysis. Trials with contact times over 250 ms were not recorded. The ICC was 0.97 (0.96–0.98) for 20-cm BDJ, 0.97 (0.96–0.98) for 40-cm BDJ, and 0.97 (0.96–0.98) for 60-cm BDJ.

Squat Jump Test. An SJ was also used to assess maximal vertical jump height performance. The SJ test was performed using an electronic contact mat system (Globus Tester) with a precision of 0.01 m. Jump height was determined using an acknowledged flight-time calculation (13, 27). During SJ, the subject was instructed to rest his hands on his hips, foot, and shoulders wide apart, adopt a flexed knee position (approximate 90 degrees) during 3 seconds (102), and followed by a maximal effort vertical jump. All subjects were instructed to land in an upright position and to bend the knees after landing. Three trials were completed, with 10–15 seconds of rest between them, and the best performance trial was used for the subsequent statistical analysis.

Countermovement Jump Test. A CMJ was used to assess maximal jump height performance requiring slow SSC action. The CMJ test was performed using an electronic contact mat system (Globus Tester) with a precision of 0.01 m. Jump height was determined using an acknowledged flight-time calculation (13). During CMJ, the subject was instructed to rest his hands on his hips, foot, and shoulders wide apart; subjects performed a downward movement (no restriction was imposed over the knee angle achieved (131) followed by a maximal effort vertical jump. All subjects were instructed to land in an upright position and to bend their knees after landing. Three trials were completed, with 10–15 seconds of rest between them, and the best performance trial was used for the subsequent statistical analysis.

20-m Sprint Time Test. Sprint times were recorded for 20-m distances. The 20-m sprint test was conducted indoors on a wooden running surface. For all sprint tests, the subject started using a crouch start and commenced sprinting with a random sonorous sound. Infrared beams were positioned at the sprint distance, 1-m over the floor, to be measured with photoelectric cell (Globus Tester). Subjects were given 2 practice trials performed at half speed after a thorough warm-up to familiarize them with the timing device. Three trials were completed, and the best performance trial was used for the subsequent statistical analysis. Three minutes of rest were permitted between 20-m trials. Times were recorded to the nearest 0.01 second.

Agility. Agility times were recorded for the Illinois agility test. The test was used to determine the ability to accelerate, decelerate, turn in different directions, and run at different angles (99). The Illinois agility test is set up with 4 cones forming the agility area (10-m long × 5-m wide). A cone was placed at each point (a) to mark the start, (b and c) to mark the turn spots, and (d) to mark the finish. Another 4 cones were placed in the center of the testing area, 3.3 m from each other. The test was conducted indoors on a wooden running surface. For all agility tests, the subject starts on the floor, face down, and begins with a random sonorous sound. The subjects must complete, as fast as possible, the agility circuit. Infrared beams were positioned at the finish point, 1-m over the floor, to take measurements with a photoelectric cell (Globus Tester). Subjects were given 2 practice trials performed at half speed after a thorough warm-up to familiarize them with the circuit and timing device. Two trials were completed, and the best performance trial was used for the subsequent statistical analysis. Three minutes of rest were permitted between agility trials. Times were reported to the nearest 0.01 second.

4.2.4. Plyometric Training Program

The PT took place 2 days per week (with at least 48 hours of rest between sessions) for the PT groups, during 7 weeks of treatment. Each session lasted 30–45 minutes. Ten minutes of standard warm-up (i.e., 5 minutes of sub maximal running and several displacements, stretching exercises for 5 minutes, 20 sub maximal vertical jumps, and 10 sub maximal longitudinal jumps) was used before the main part of the training session. The plyometric exercises consisted of BDJ, with a total of 60 BDJ per session (2 series of 10 jumps from a 20-cm box, 2 series of 10 jumps from a 40-cm box, and 2 series of jumps from a 60-cm box) for the MVG and MVG_{HS} groups, and a total of 120 BDJ per session (4 series of 10 jumps from a 20-cm box, 4 series of 10 jumps from a 40-cm box, and 4 series of jumps from a 60-cm box) for the HVG group. The rest period between repetitions was approximately of 5 seconds and between series was 1.5 minutes. The control group did not perform any training intervention. This group underwent the same testing protocols as the other groups.

The training was performed on a wood gymnasium floor with a restitution coefficient of 0.8 (MVG_{HS}) or on a 3-cm thick athletic mat (27) with a restitution coefficient of 0.5 (MVG and HVG). The subjects were instructed to place their hands on their hips and step off the platform with the leading leg straight to avoid any initial upward propulsion, ensuring a drop height of 20, 40, and 60 cm. They were instructed to jump for maximal height and minimum contact time in every jump. These instructions were intended to maximize reactive strength. A researcher was always present during training sessions, motivating subjects to give their maximum effort in each jump.

4.2.5. Statistical Analyses

Descriptive statistics (mean ± SD) for the different variables were calculated. Before and after intervention values for the dependent variables were analyzed to determine if the distributions were normal using the Shapiro-Wilk Normality test. To determine the effect of different PT volumes and surfaces on explosive strength adaptations, a 2-way variance analysis with repeated measurements (4 groups × 2 times) was applied. When a significant F value was achieved across time or between groups, Fisher's least significant difference post hoc procedures were performed to locate the pairwise differences between the means. The α level was set at $p<0.05$ for statistical significance. All statistical calculations were performed using STATISTICA statistical package (Version 8.0; Stat Soft, Inc, Tulsa, OK, USA).

4.3. Study III

4.3.1. Experimental Approach to the Problem

It was examined the ability of an in-season short-term PT program, implemented as a substitute for some soccer drills within regular soccer practice, to improve explosive and endurance performance compared to soccer practice only. To do this, it was compared the effects of 7 weeks of PT in two groups of subjects, formed from young male soccer players; one group followed the modified soccer practice (TG) and the other followed the regular soccer practice (CG). Some initial tests were executed to establish a baseline. Tests were related to different jump variables, acceleration, agility, endurance, kicking, and anthropometrics. This was a randomized controlled trial. The assigned groups were determined by a chance process and could not be predicted.

4.3.2. Subjects

Initially 121 male soccer players between 10 and 16 years of age fulfill the inclusion criteria to participate in the study. Subjects were recruited from 4 different soccer teams with similar competitive schedule (one official competitive game per week) and soccer drills used during their two weekly training sessions. Soccer players full-filled the following inclusion criteria: 1) more than 2-year background of systematic soccer training and competition experience; 2) continuous soccer training in the last 6 months, 3) no PT experience in the last 6 months, 4) no background in regular strength training or competitive sports activity that involved any kind of jumping training exercise during the treatment. To be included in the final analyses participants were required to complete all the familiarization sessions, training sessions and attend to all measurements sessions. As a result of these requirements 45 subjects were removed from the study. Therefore 76 male soccer players were included for the final analyses. The 76 subjects measured where randomly divided in two groups: control group (CG; N = 38) and PT group (TG; N = 38). Subject characteristics are provided in Table 1. Institutional Review Board approval for our study was obtained, and all subjects (and their parents or guardians) were carefully informed about the experiment procedures, and about the possible risk and benefits associated with participation in the study, and an appropriate signed informed consent/assent document has been obtained pursuant to law before any of the tests were performed. We comply with the human and animal experimentation policy statements guidelines of the American College of Sport Medicine. Sample size was computed according to changes observed in plyometric (i.e., reactive strength index) performance ($\Delta = 0.3$ mm·ms^{-1}; SD = 0.35) in a group of young adolescents submitted to the same training program applied in this study (19). A total of 8 participants per group would yield a power of 80% and a = 0.05.

Table 1. Subject characteristics at the start of the 7-week period (mean ± SD).

	Control group (N = 38)	Training group (N = 38)
Age (y)	13.2 ± 1.8	13.2 ± 1.8
Genital Tanner stage	3.7 ± 1.0	3.7 ± 1.1
Pubic Hair Tanner stage	3.6 ± 1.1	3.6 ± 1.1
Mass (kg)	47.4 ± 11.9	47.9 ± 10.0
Height (cm)	153 ± 12	154 ± 12
BMI ($m.kg^{-2}$)	19.9 ± 2.3	19.9 ± 1.7
Session rating of perceived exertion	312 ± 123	334 ± 151
Soccer experience (y)	4.1 ± 1.8	4.4 ± 1.6

No significant difference between groups and within groups before and after the 7-week period.

4.3.3. Testing Procedures

Subjects followed a familiarization session of 90 min prior to testing to reduce any learning effects. Standardized tests of explosive actions were scheduled >48 hours following a competition or hard physical training to minimize the influence of fatigue and performed under similar weather, time and field conditions before and immediately after the 7-week period over two days. On day one, players characteristics (height, body mass and self-assessed Tanner pubic hair and genital stage) and performance test were conducted in the following order: countermovement jump (CMJ), 20 (RSI20) and 40 (RSI40) cm drop jump reactive strength index, five alternated leg bounds test (MB5), 20-m sprint (20m), and Illinois agility test. On day two, maximal kicking test for distance (MKD) followed by a 2.4 km time trial were performed. All tests were administered in the same order pre- and post-training in the same sporting clothes and recorded by the same investigators. In addition, all participants (and their parents or guardians) were instructed to have a good night's sleep (≥9 h) before each testing day, to avoid drinking or eating at least 2-3 h before measurements. All participants were motivated to give their maximum effort during performance measurements. At least two minutes of rest was allowed between each trial to reduce fatigue effects. While waiting, participants performed low-intensity activity to maintain physiological readiness for the next test. The best score of three trials was recorded for all performance tests apart for the single 2.4 km time trial. High intraclass correlation coefficients were obtained for the different performance test, varying between 0.81 to 0.98.

Anthropometrics and Maturity. Height was measured using a wall-mounted stadiometer (Butterfly, Shanghai, China) recorded to the nearest 0.5 centimeter, body mass was measured to the nearest 0.1 kg using a digital scale (BC-554 Ironman Body Composition Monitor, Tanita, Illinois, USA) and body mass index (BMI) was calculated ($kg{\cdot}m^{-2}$). Maturity was determined by self-assessment of Tanner stage (143).

Vertical Jump Tests. Testing included the execution of maximal CMJ, RSI20 and RSI40. All jumps were performed on a mobile contact mat (Ergojump, Globus, Codogne, Italy) with arms akimbo. Take-off and landing was standardized to full knee and ankle extension on the same spot. The participants were instructed to maximize jump height and minimize ground contact time during the RSI20 and RSI40 after dropping down from a 20 cm and 40 cm drop box, respectively. The RSI variable was calculated as previously reported (82).

Multiple 5 Bounds Test. The multiple 5 bounds test (MB5) was started from a standing position and performed a set of 5 forward jumps with alternative left- and right-leg contacts to cover the longest distance possible. The distance of the MB5 was measured to the nearest 0.5 cm using a tape measure (95).

20-m Sprint and Illinois Agility Test. The sprint time was measured to the nearest 0.01 s using single beam infrared reds photoelectric cells (Globus Italia, Codogne, Italy). The starting position was standardized to a still split standing position with the toe of the preferred foot forward and behind the starting line. Sprint start was given by a random sound which trigger timing. The photoelectric signal was positioned at 20 m and set approximately 0.7 m above the floor (i.e. hip level) to capture the trunk movement rather than a false trigger from a limb. The Illinois agility test has been described and its reliability addressed elsewhere (48). The timing system and procedures where the same as the 20-m sprint, except that subjects started lying on their stomach on the floor with their face down.

Maximal Kicking Distance Test. After a standard warm-up, each player kicked a new size five soccer ball (Nike Seitiro, FIFA certified) (34) for maximal distance on a soccer field, according to previous recommendations (8). Two markers were placed on the ground side by side to define the kick line. Participants performed a maximal instep kick with their dominant leg after a run up of two strides. A 75 m metric tape was placed between the kicking line and across the soccer field. An assessor was placed near the region where the ball land after the kick to mark the point of contact and to measure the distance kicked. The distance was measured to the nearest 0.2 m. All measurements were completed with a wind velocity <20 $km \cdot h^{-1}$ (Chilean Meteorological Service, Santiago, Chile). Previous studies have reported a high reliability of similar soccer kicking test (88, 100).

2.4 km Time Trial. After a warm-up of two laps (800 m) and 4 min rest, players performed six laps of a 400 m outdoor dirt track timed to the nearest second using a stopwatch. The wind velocity at all times was less than 9.9 $km \cdot h^{-1}$, the relative humidity was between 50-70%, and the temperature was between 15-20°C (Chilean Meteorological Service, Santiago, Chile). Motivation was considered maximal as this test was conducted as part of selection process.

4.3.4. Plyometric Training Program

The study was completed during the mid-portion of their competition period. Previous to the competitive period subjects completed two months of summer pre season training. The control group did not perform the PT, but performed their usual soccer-training. A detailed description of the usual soccer-training applied during the competition period is depicted in Table 2. To know the training load during the intervention, the session rating of perceived exertion (RPE) was determined (Table 1) by multiply the soccer training duration (minutes) by session RPE as described previously in young soccer players (63). We used the Chilean translation of the 10 point category ratio scale (CR10-scale) modified by Foster et al. (37).

Table 2. Usual soccer training session of young soccer players during intervention.

Exercise	Duration (min)
Technical drills (ball control; ball pass; ball conduction and dribbling; ball kicking; ball heading)	20
Tactical drills (defensive drills; offensive drills; corner kicks situations; penalty kicks)	20
Small-sided games with or without goal keeper, and with or without change of soccer rules (e.g. one touch pass; only heading goals)	20
Simulated competitive games	30

Before the initiation of the training period, the TG subjects were instructed on proper execution of all the exercises included in the program. During intervention, the TG removed the technical drills (i.e. ball control; ball pass; ball conduction and dribbling; ball kicking; ball heading exercises) and replace them with plyometric drills within the usual 90-minute practice twice per week for seven weeks. This time frame and/or number of sessions are higher (17, 84, 135, 137) or very similar (23, 95) to those previously reported to induce significant explosive adaptations in young soccer players. All plyometric sessions lasted 21 minutes and were performed just after the warm-up to ensure that the players were in a rested state and gain optimal benefits from the specific program, according to the training principle of priority (70). Plyometric drills included two sets of 10 repetitions of drop jumps from 20, 40 and 60 cm (i.e. 60 contacts) performed on a grass soccer field. Exercise intensity was determined as high (95) and exercise volume low (i.e. total ground contacts). Although we did not increase the training volume during the 7-weeks period, as we used high intensity plyometric exercises performed with maximal effort, an adequate training stimulus was applied during each plyometric session, as previously demonstrated in soccer players (84).

The rest period between repetitions and sets was of 15 seconds (117) and 90 seconds, respectively, as previous research had demonstrated that this is an adequate rest interval for this type of training. The subjects were instructed to place their hands on their hips and step off the platforms with the supporting leg straight to avoid any initial upward propulsion or sinking, ensuring a drop height of 20, 40, and 60 cm. Participants were instructed to jump for maximal height and minimum contact time every jump to maximize reactive strength (i.e. bounce drop jumps). As players did not have any history of formal plyometrics, all exercises were supervised and particular attention was paid to demonstration and execution, giving maximal motivation to athletes during each jump. Training sessions were separated with a minimum of 48 hours (including games), to ensure the players were always fresh to train (95). Aside from the formal training intervention, all participants attended to their regular physical education classes.

4.3.5. Statistical Analyses

All values are reported as mean ± standard deviation (SD). Relative changes (%) in performance and standardized effects are expressed with 90% Confidence Limits (CL). Normality and homoscedasticity assumptions for all data before and after intervention were checked respectively with Shapiro-Wilk and Levene tests. To determine the effect of intervention (i.e. plyometric training) on explosive strength adaptations, a 2-way variance analysis with repeated measurements (2 groups × 2 times) was applied. When a significant F value was achieved across time or between groups, Tukey´s post hoc procedures were performed to locate the pairwise differences between the means. The α level was set at $p<0.05$ for statistical significance. All statistical calculations were performed using STATISTICA statistical package (Version 8.0; Stat Soft, Inc, Tulsa). In addition to this null hypothesis testing, these data were also assessed for clinical significance using an approach based on the magnitudes of change. Threshold values for assessing magnitudes of standardized effects (SE - changes as a fraction or multiple of baseline standard deviation) were 0.20, 0.60, 1.2 and 2.0 for small, moderate, large and very large respectively (59). The effect was deemed unclear when the chance of benefit (a standardized improvement in performance of >0.20) was sufficiently high to warrant use of the intervention, but the risk of impairment was unacceptable. Such unclear effects were identified as those with an odds ratio of benefit to impairment of <66, a ratio that corresponds to an effect that is borderline possibly beneficial (25% chance of benefit) and borderline most unlikely detrimental (0.5% risk of harm). The effect was otherwise clear and reported as the magnitude of the observed value (59).

4.4. Study IV

4.4.1. Experimental Approach to the Problem

It was examined the ability of an in-season short-term PT program using different rest intervals between sets, and implemented as a substitute for some soccer drills within regular soccer practice, to improve explosive actions compared to soccer practice only. To do this, it was compared the effects of 7 weeks of PT in 4 groups of subjects, formed from young male soccer players; one group followed the regular soccer practice (CG), and the others followed a PT program using 30 s (G30), 60 s (G60), or 120 s (G120) of rest between PT series. Some initial tests were executed to establish a baseline. Tests were related to different jump variables, acceleration, agility, kicking, and anthropometrics. This was a randomized controlled trial. The assigned groups were determined by a chance process and could not be predicted.

4.4.2. Subjects

Initially 90 male participants between 8 and 14 years of age fulfill the inclusion criteria to participate in the study. Participants were recruited from an amateur soccer team, thus all athletes were submitted to the same soccer drills (2 training sessions per week, in addition to one or two competitive games). Athletes also participate in their regular weekly physical education classes. To be included in the final analyses participants were required to complete >90% of all the training sessions and attend to all measurements sessions. As a result of these requirements 36 participants were removed from the study. Therefore 54 young male soccer players were included for the final analyses. Participants were randomly assigned in four groups: CG (n = 15), G30 (n = 13), G60 (n = 14), and G120 (n = 12) (initial characteristics are shown in Table 3). None of the participants had any background in regular weight training or competitive sports that involved any of the training methods used in the investigation. From a practical and scientific point of view, the interest of the present study was focused on these participants because: a) plyometric exercises are commonly used during initial phases of children's training and playing approaches, b) require reduced physical space, time, and equipment, c) may induce important adaptations in young soccer players (28, 95).

Table 3. Subject characteristics at the start of the 7-week period. Data are means (±SD).

Variable	Control (n=15)	G30 (n=13)	G60 (n=14)	G120 (n=12)
Pubic hair Tanner stage	2.4 (1.0)	2.2 (1.0)	2.3 (1.1)	2.3 (1.2)
Genital Tanner stage	2.2 (0.6)	2.4 (0.8)	2.2 (0.6)	2.3 (0.9)
Age (y)	10.1 (2.0)	10.4 (2.0)	10.4 (2.3)	10.3 (2.3)
Height (m)	1.43 (0.1)	1.41 (0.1)	1.41 (0.1)	1.42 (0.1)
Body mass (kg)	39.0 (9.3)	37.0 (7.0)	37.2 (6.1)	38.0 (10.0)
Soccer experience (y)	3.4 (1.6)	3.1 (1.9)	3.6 (1.5)	3.0 (1.3)
Session rating of perceived exertion	369 (180)	328 (201)	343 (166)	378 (159)

G30, G60, and G120: 30 s, 60 s, and 120 s rest interval groups, respectively

Exclusion criteria included participants with 1) potential medical problems or a history of ankle, knee, or back pathology in the 3 months prior to the study, 2) medical or orthopedic problems that compromised their participation or performance in the study, and 3) any lower extremity reconstructive surgery in the past two years or unresolved musculoskeletal disorders. Individuals were not eliminated if they had been taking vitamins, minerals, or related natural supplements (other than creatine monohydrate). All participants (and their parents or guardians) were fully informed about the experimental procedures and possible risks and benefits associated with the study. They were then invited to sign an informed consent document before any of the tests were performed. The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Department of Physical Activity Sciences from University of Los Lagos, Osorno, Chile.

4.4.3. Testing Procedures

All tests were carried out between 18:00-20:00 h. All participants (and their parents or guardians) were instructed to a) have a good night's sleep (≥9 h) before each testing day, b) avoid drinking or eating at least 2-3 h before measurements, c) use the same sport shoes during the pre and post intervention testing. All participants were motivated to give their maximum effort during performance measurements. For performance measurements, participants were carefully familiarized with the test procedures during two practice sessions per week during two weeks, performing 20 min of technique training for the testing exercises to be used during measurement. The participants also completed several explosive type actions during these four sessions to become familiar with the exercises used during training. Participants did not report subjective feelings of muscle damage after the familiarization sessions. Considering that the capacity of soccer players to produce varied forceful and explosive actions, such as sprinting, jumping, tackling, kicking, turning, and changing pace, highly influences soccer match performance (118), the following performance test were applied: CMJ, RSI20, RSI40, MKD, 20-m; and L-run agility test. Ten minutes of standard warm-up (5 minutes of sub maximal running with several displacements, and 2 sub maximal jump exercises of 20 vertical jumps and 10 longitudinal jumps) were executed before each testing day.

Anthropometrics and Maturity. Height was measured using a wall-mounted stadiometer (Butterfly, Shanghai, China) recorded to the nearest 0.5 cm, body mass was measured to the nearest 0.1 kg using a digital scale (BC-554 Ironman Body Composition Monitor, Tanita, Illinois, USA) and body mass index (BMI) was calculated ($kg \cdot m^{-2}$). Maturity was determined by self-assessment of Tanner stage (143).

Jumps. Testing included the execution of maximal CMJ, RSI20, and RSI40. All jumps were performed on a mobile contact mat (Globus, Codogne, Italy) with arms akimbo. Take-off and landing was standardized to full knee and ankle extension on the same spot. The participants were instructed to maximize jump height and minimize ground contact time during the RSI20 and RSI40 after dropping down from a 20 and 40 cm drop box. The RSI20 and RSI40 were calculated as previously reported (Young et al., 2002).

Sprint. The sprint time was measured to the nearest 0.01 s using single beam infrared reds photoelectric cells (Globus Italia, Codogne, Italy). The starting position was standardized to a still split standing position with the toe of the preferred foot forward and behind the starting line. Sprint start was given by a random sound which triggers timing. The photoelectric signal was positioned at 20 m and set approximately 0.7 m above the floor (i.e. hip level) to capture the trunk movement rather than a false trigger from a limb.

Agility Run. Agility times were recorded from the L-run agility test, following previously described instructions (39). The timing system and procedures where the same as the 20-m sprint.

Kicking Distance. After a standard warm-up, each player kicked a new size five soccer ball (Nike Seitiro, FIFA certified - (34) for maximal distance on a soccer field, according to previous indications (8). Basically, two markers were placed on the ground side by side to define the kick line. Participants performed a maximal instep kick with their dominant leg after a run up of two strides. A 75 m metric tape was placed between the kicking line and across the soccer field. An assessor was placed near the region where the ball land after the kick to mark the point of contact and to measure the distance kicked. The distance was measured to the nearest 0.2 m. All measurements were completed with a wind velocity <20 $km \cdot h^{-1}$ (Chilean Meteorological Service, Santiago, Chile).

4.4.4. Plyometric Training Program

The intervention took place during the competitive period. During the intervention participants kept their usual soccer training (i.e. two weekly training sessions of 90 min, consisting in 30 min of technical-tactical exercises, 30 min of small-sided games, and 30 min of simulated competitive games) and competition schedule. The PT was completed two days per week for the PT groups, with 48 hours of rest between sessions as previously recommended (30, 141), and just after the warm-up to ensure that the players were in a rested state and gain optimal benefits from the specific program, according to the priority training principle (70). The same warm up was completed by the CG and plyometrically trained groups. While the CG keeps their regular soccer drills, the G30, G60, and G120 groups replaced the technical-tactical drills by plyometric exercises. After the plyometric drills, participants from the G30, G60, G120, and CG completed the same soccer training sessions. To know the training load during the intervention, the session rating of perceived exertion (RPE) was determined (Table 3) by multiply the soccer training duration (minutes) by session RPE as described previously in young soccer players (63). We used the Chilean translation of the 10 point category ratio scale (CR10-scale) modified by Foster et al. (37).

Participants were instructed to jump for maximal height and minimum contact time every jump to maximize reactive strength (i.e. bounce drop jumps). Athletes complete a total of 60 jumps per session (2 sets of 10 jumps from 20, 40, and 60 cm boxes). As players did not have any history of formal plyometrics, all exercises were supervised and particular attention was paid to demonstration and execution, giving maximal motivation to athletes during each jump. Although we did not increase the training volume during the 7-weeks period, as we used high intensity plyometric exercises performed with maximal effort, an effective and safe training stimulus was applied during each plyometric session, as previously demonstrated in similar plyometric training interventions in young boys (19) and soccer players (135). The exercise were completed 2 times per week, for a total of 7 weeks. This time frame and/or number of sessions are higher (84, 135, 137) or very similar (17, 23, 95) to those previously reported to induce significant explosive adaptations in young soccer players and youths (19).

The different rest periods between sets of plyometric drills for the three experimental groups were choose based on previous recommendations (3-4, 117), corresponding to 30 s, 60 s, and 120 s of rest between sets for the G30, G60 and G120 groups, respectively. The rest between repetitions was of 15 s (117). A low intensity active interset and inter repetition rest was used to favor recovery (11).

To assure the safety of plyometric sessions, subjects were asked to classify their actual pain level though a visual analog scale (VAS). A continuous line of 10 cm were presented to athletes with the Spanish words for “no pain” in the cm 0 and with the Spanish word for “maximal pain” in the cm 10. Subjects were asked to classify their pain while they were sitting. Similar protocols had been applied previously (47, 65, 86). We measure the intensity of muscle pain from the lower extremities before the first session of plyometric training, immediately after, 24h, 48h, 72h, and 96h after the first session. Also, during the last week of training we repeated the protocol. Subjects report relatively a low pain level (between 0-2). This seems common in youths (29, 85-86).

4.4.5. Statistical Analyses

All values were reported as mean ± SD. Relative changes (%) in performance and standardized effects (SE) are expressed with 90% confidence limits (CL). Normality and homoscedasticity assumptions for all data before and after intervention were checked respectively with Kolmogorov-Smirnov and Levene tests. To determine the effect of intervention on performance adaptations, a 2-way variance analysis with repeated measurements (4 group’s × 2 times) was applied. When a significant F value was achieved across time or between groups, Tukey post hoc procedures were performed to locate the pairwise differences between the means. The α level was set at $p<0.05$ for statistical significance. In addition to this null hypothesis testing, data was also assessed for clinical significance using an approach based on the magnitudes of change.

Threshold values for assessing magnitudes of SE (changes as a fraction or multiple of baseline standard deviation) were 0.20, 0.60, 1.2 and 2.0 for small, moderate, large and very large respectively (59).

4.5. Study V

4.5.1. Experimental Approach to the Problem

It was examined the ability of an in-season short-term PT program using different rest intervals between training sessions, and implemented as a substitute for some soccer drills within regular soccer practice, to improve explosive and endurance performance actions compared to soccer practice only. To do this, it was compared the effects of 6 weeks of PT in 3 groups of subjects, formed from young male soccer players; one group followed the regular soccer practice (CG), and the others followed a PT program using 24 h (PT24), or 48 h (PT48) of rest between PT sessions. Some initial tests were executed to establish a baseline. Tests were related to different jump variables, acceleration, agility, endurance, flexibility, and anthropometrics. This was a randomized controlled trial. The assigned groups were determined by a chance process and could not be predicted.

4.5.2. Subjects

Initially 189 subjects that fulfill the inclusion criteria were chosen to participate in the study. To be included in the final analyses participants were required to complete all the training sessions and attend to all measurements sessions. As a result of these requirements 23 subjects were removed from the study. Therefore 166 male soccer players were included for the final analyses. The 166 subjects initially measured where divided in three groups: control (CG; N = 55), PT with 24 h (PT24; N = 54) and 48 h (PT48; N = 57) of rest between training sessions. Mean values ± SD for groups characteristics are provided in Table 4. The study was conducted during autumn in subjects of 10 to 17 years of age.

Table 4. Descriptive data of young soccer athletes.

	CG (N=55)	**PT24 (N=54)**	**PT48 (N=57)**
Age (years)	14.0±2.3	14.2±2.2	14.1±2.2
Height (cm)	160.3±13.1	158.0±12.4	159.4±12.3
Body mass (kg)	52.1±12.1	50.3±12.1	51.8±12.2
IMC ($kg \cdot m^{-2}$)	19.9±2.0	19.8±2.2	20.0±2.1
Genital Tanner stage	3.9±1.2	4.1±1.1	3.9±1.2
Pubic hair Tanner Stage	3.8±1.2	3.9±1.1	3.9±1.2
Soccer experience (years)	5.3±2.0	5.0±1.9	5.4±2.4
Session rating of perceived exertion	432 ± 275	463 ± 229	451 ± 308

Subjects were recruited from two different amateur soccer teams with similar competitive schedule (1 game per week) and similar soccer drills (2 sessions per week) resulting in similar soccer-specific weekly training load for all groups in the study design. To know the training load during the intervention, the session rating of perceived exertion (RPE) was determined (Table 4) by multiply the soccer training duration (minutes) by session RPE as described previously in young soccer players (63). We used the Chilean translation of the 10 point category ratio scale (CR10-scale) modified by Foster et al. (37).

Soccer players full-filled the following inclusion criteria: 1) more than 2-year background of systematic soccer training and competition experience; 2) continuous soccer training in the last 6 months, 3) no PT experience in the last 6 months, 4) no background in regular strength training or competitive sports activity that involved any kind of jumping training exercise during the treatment. Institutional Review Board approval for our study was obtained, and all subjects (and their parents or guardians) were carefully informed about the experiment procedures, and about the possible risk and benefits associated with participation in the study, and an appropriate signed informed consent/assent document has been obtained pursuant to law before any of the tests were performed. We comply with the human and animal experimentation policy statements guidelines of the American College of Sport Medicine.

4.5.3. Testing Procedures

Subjects followed a familiarization period prior to testing to reduce any learning effects. Standardized tests were scheduled >48 hours following a competition or hard physical training, and were completed in the same order, at the same time of day, in the same indoor venue, with the same sporting clothes and by the same investigator before and immediately after the 6-week intervention period. In addition, all participants (and their parents or guardians) were instructed to have a good night's sleep (≥9 h) before each testing day, to avoid drinking or eating at least 2-3 h before measurements. All participants were motivated to give their maximum effort during performance measurements.

On day one, players' characteristics (age, height, weight, self-assessed Tanner pubic hair and genital stage, and soccer experience) were assessed. On day two the SJ and CMJ test were performed. The third day, the RSI20 and BLJ were assessed. The fourth day, 20-m sprint and running 10 x 5-m agility test were conducted. On the fifth day, the MST and the SR were undertaken. At least two minutes of rest was allowed between each trial to reduce the effects of fatigue. While waiting, participants performed low-intensity activity to maintain physiological readiness for the next test. The best score of three trials was recorded for all performance tests, apart for the single MST.

Anthropometrics and Maturity. Height was measured using a wall-mounted stadiometer (Butterfly, Shanghai, China) recorded to the nearest 0.5 centimeter; body mass was measured to the nearest 0.1 kg using a digital scale (BC-554 Ironman Body Composition Monitor, Tanita, Illinois, USA) and body mass index (BMI) was calculated ($kg \cdot m^{-2}$). Maturity was determined by self-assessment of Tanner stage (143).

Vertical Jump Tests. Testing included the execution of maximal SJ, CMJ and RSI20. All jumps were performed on a mobile contact mat (Globus, Codogne, Italy) with arms akimbo. Take-off and landing was standardized to full knee and ankle extension on the same spot. The participants were instructed to maximize jump height and minimize ground contact time during the RSI20 after dropping down from a 20 cm drop box. The RSI was calculated as previously reported (82).

Broad Long Jump Test. The BLJ was used to assess maximal jump performance in the horizontal plain. The test was performed using a 5 m fiberglass metric tape laid on a wooden floor. Subjects were instructed to jump positioning (behind the starting line) their foot shoulders wide apart and to perform a fast downward movement (approximately 120-degree knee angle) followed by a maximal effort horizontal jump. Subjects were instructed to bend their knees after landing. Distance was measured from the starting line to the point where the heels of the subjects make contact with the ground after landing.

20-m Sprint Test. The sprint time was measured to the nearest 0.01 s using single beam infrared red photoelectric cells (Globus, Codogne, Italy). The starting position was standardized to a still split standing position with the toe of the preferred foot forward and behind the starting line. Sprint start was given by a random sound which triggers timing. The photoelectric signal was positioned at 20 m and set approximately 0.7 m above the floor (i.e. hip level) to capture the trunk movement in order to avoid a false trigger from a limb.

Running 10 x 5-m Agility Test. The test was conducted as previously described (61). Markers were set at 5 m distance. The examinee was asked to run from one marker to another 10 times, with the fastest possible result and direction change. The examinee had to pass the marked space with both legs. The results were in seconds, determined with hand-held chronometer.

20-m Multi-Stage Shuttle Run Test (MST). The MST was conducted as previously described (6). Briefly, players ran back and forth between two lines, spaced 20-m apart, in time with the "beep" sounds from a compact disc. Each successful run of the 20-m distance was a completion of a shuttle. The "beep" sounded at a progressively increasing pace with every minute of the test, and the athlete had to increase speed accordingly. The athlete was warned if he did not reach the end line in time once. The test was terminated when the examinee i) could not follow the set pace of the "beeps" for two successive shuttles, and/or ii) stopped voluntarily. The scores was expressed as the last minute that the player complete (74).

Sit and Reach Test. For the SR test, similar instruments and protocols were used as previously reported (79). Briefly, a scale calibrated in cm was placed on the top surface of a SR box. The test was performed by having athletes sitting on the floor. The athlete's feet were placed flat against the SR box, separated approximately by 40 cm. Players then slowly reached forward towards their toes, as far as possible, while keeping their knees, arms, and fingers fully extended, with palms down and placing their right hand over the left, with long fingers even, holding the position of maximal reach for 2 s. The precision of the measurement was 0.5 cm.

4.5.4. Plyometric Training Program

The study was completed in autumn, during the mid-portion of their competition period. The control group did not perform the PT, but performed their usual soccer-training (technical-tactical exercises, small-sided games, simulated competitive games, and basic conditioning exercises). The PT groups performed plyometric drills as a substitute for some soccer drills within the usual 120-min practice twice per week for six weeks. This time frame and/or number of sessions are higher (84, 137), the same (84, 135) or very similar (23, 95) to those previously reported to induce significant explosive adaptations in young soccer players and youths (19). Plyometric volume was increased 20% per week. As players did not have any history of formal plyometrics, before beginning the training period they were instructed on how to properly execute all the exercises to be done during this period. In addition, all training sessions were supervised and particular attention was paid to demonstration and execution. PT sessions were separated with 24 h for PT24 and with 48 h for PT48. All plyometric sessions lasted approximately 30 min and were performed just after the warm-up. Aside from the formal training intervention, all participants attended their regular physical education classes. PT24 and PT48 completed the same amount of total jumps during intervention, used the same surface (grass soccer-field) and time of day (afternoon) for training, with the same rest intervals between jumps and series. Half of the plyometric volume corresponds to cyclic (emphasizing the maximization of reactive strength), and the other half to acyclic jumps (emphasizing maximal jump height or distance). The combination of multilateral, multidirectional, cyclic and acyclical plyometric drills was based on previous suggestions (25, 94-95, 123). The rest interval between series was of 120 s, and between acyclic jumps was of approximately 15 s, as previously recommended (117). The same 13 exercises were completed by both groups. All exercises were performed as a countermovement jump with arm swing (i.e. stretch shortening cycle involvement). In addition, both groups completed 2 sets of 10 repetitions of high intensity bounce drop jumps from 20 cm high boxes. A detailed description of the 6-week training program is depicted in Table 5.

Table 5. Six weeks plyometric training program

Exercises*	**Set × Repetitions**					
	Week 1	**Week 2**	**Week 3**	**Week 4**	**Week 5**	**Week 6**
Cyclic horizontal left leg	2 × 5	2 × 6	2 × 7	2 × 8	2 × 9	2 × 10
Acyclic horizontal left leg	2 × 5	2 × 6	2 × 7	2 × 8	2 × 9	2 × 10
Cyclic horizontal right leg	2 × 5	2 × 6	2 × 7	2 × 8	2 × 9	2 × 10
Acyclic horizontal right leg	2 × 5	2 × 6	2 × 7	2 × 8	2 × 9	2 × 10
Cyclic vertical left leg	2 × 5	2 × 6	2 × 7	2 × 8	2 × 9	2 × 10
Acyclic vertical left leg	2 × 5	2 × 6	2 × 7	2 × 8	2 × 9	2 × 10
Cyclic vertical right leg	2 × 5	2 × 6	2 × 7	2 × 8	2 × 9	2 × 10
Acyclic vertical right leg	2 × 5	2 × 6	2 × 7	2 × 8	2 × 9	2 × 10
Cyclic bilateral vertical	2 × 5	2 × 6	2 × 7	2 × 8	2 × 9	2 × 10
Acyclic bilateral vertical	2 × 5	2 × 6	2 × 7	2 × 8	2 × 9	2 × 10
Cyclic bilateral horizontal	2 × 5	2 × 6	2 × 7	2 × 8	2 × 9	2 × 10
Acyclic bilateral horizontal	2 × 5	2 × 6	2 × 7	2 × 8	2 × 9	2 × 10
Bounce drop jumps 20cm	2 × 10	2 × 10	2 × 10	2 × 10	2 × 10	2 × 10

*: denotes that the order of exercises execution was randomized each training session.

4.5.5. Statistical Analyses

All values were reported as mean ± SD. Relative changes (%) in performance and standardized effects (SE) are expressed with 90% confidence limits (CL). Normality and homoscedasticity assumptions for all data before and after intervention were checked respectively with Shapiro-Wilk and Levene tests. To determine the effect of intervention on performance adaptations, a 2-way variance analysis with repeated measurements (3 group's × 2 times) was applied. When a significant F value was achieved across time or between groups, Sheffe post hoc procedures were performed to locate the pairwise differences between the means. The α level was set at $p<0.05$ for statistical significance. In addition to this null hypothesis testing, data was also assessed for clinical significance using an approach based on the magnitudes of change. Threshold values for assessing magnitudes of SE (changes as a fraction or multiple of baseline standard deviation) were 0.20, 0.60, 1.2 and 2.0 for small, moderate, large and very large respectively (59).

5. RESULTS AND DISCUSSION

5.1. Study I

Because after the analysis of variance no significant differences were detected between men and women in percentage change in any of the test variables from before to after training, both genders were pooled in each group, as previously suggested (120). The main finding of the present study was that the combination of high intensity plyometric exercises (i.e. BDJ) and running endurance training induce significant increases in explosive-strength and running endurance performance after 6 weeks of moderate volume PT in competitive middle and long distance runners (Table 6). These results suggest that to optimize running endurance performance and explosive-strength adaptations in middle and long distance runners, a PT program should be added to their regular running training program.

Table 6. Before and after intervention anthropometric and performance characteristics (mean ± SD) and % change of explosive-strength trained (TG) and non-trained (CG) competitive middle and long distance runners.

	CG (N = 15; 10 men)			TG (N = 17; 9 men)		
	Before	After	%[¥]	Before	After	%
Body mass (kg)						
Combined	59.8±6.1	59.9±6.4	0.2 (-0.7 to 0.4)	60.0±3.8	60.7±4.1	1.2 (0.2 to 4.4)
Men	63.2±1.5	63.3±2.3		61.1±3.4	61.8±3.8	
Women	56.4±1.8	56.4±0.5		59.1±3.7	60.0±4.0	
Body mass index (kg·m^{-2})						
Combined	21.5±0.8	21.5±0.7	0 (-0.2 to 0.8)	21.9±1.4	22.2±1.4	1.4 (0.3 to 4.8)
Men	21.6±0.7	21.5±0.7		21.7±1.3	22.0±1.1	
Women	20.9±0.9	21.0±0.4		22.0±1.3	22.5±1.6	
20-m sprint time test (s)						
Combined	3.97±0.2	3.94±0.4	-0.8 (-2.8 to 1.4)	3.92±0.3	3.83±0.3*¶	-2.3 (-5.8 to – 0.9)
Men	3.87±0.1	3.83±0.2		3.80±0.1	3.71±0.1	
Women	4.20±0.1	4.17±0.2		4.03±0.3	3.93±0.3	
2.4 km run time trial (min)						
Combined	8.0±0.9	7.9±0.9	-1.3 (-2.9 to 0.3)	7.6±0.7	7.3±0.8*¶	-3.9 (-9.1 to -1.1)
Men	7.2±0.7	7.1±0.8		7.2±0.2	6.9±1.2	
Women	8.7±0.3	8.6±0.4		8.3±0.4	8.0±0.5	
CMJA (cm)						
Combined	34.1±7.1	36.3±8.1	6.5 (-5 to 12)	36.1±5.6	39.3±7.0& δ	8.9 (3.1 to 19.6)
Men	37.0±5.8	39.9±4.1		38.1±3.7	42.5±3.6	
Women	28.2±0.3	29.4±1.5		33.9±6.0	36.1±6.6	
RSI20 (cm·ms^{-1})						
Combined	0.157±0.037	0.144±0.030	-8.3 (-10.9 to -4.3)	0.157±0.049	0.177±0.044&δ	12.7 (2.2 to 28)
Men	0.169±0.038	0.154±0.028		0.167±0.042	0.190±0.033	
Women	0.143±0.026	0.130±0.018		0.145±0.050	0.161±0.033	
RSI40 (cm·ms^{-1})						
Combined	0.166±0.047	0.156±0.046	-6 (-10 to 0.8)	0.156±0.041	0.182±0.051&¶	16.7 (3.4 to 33.2)
Men	0.179±0.041	0.169±0.023		0.168±0.032	0.197±0.034	
Women	0.152±0.037	0.141±0.010		0.139±0.048	0.160±0.023	

[¥] Values between parenthesis reflect 90% confidence limits. * denotes significant difference with the corresponding before value ($P<0.01$); [&] denotes significant difference with the corresponding before value ($P<0.001$); [¶] denotes significant difference with the CG ($P<0.05$). [δ] denotes significant difference with the CG ($P<0.01$). RSI20 and RSI40: 20 and 40 cm reactive strength index, respectively. CMJA: countermovement jump with arms.

The TG exhibited a relative reduction in 2.4 km time three times greater than that of the CG (-3.9% vs. -1.3%, respectively) (Table 6). Although the running performance has a structural basis (145) (i.e. low BMI are commonly observed among middle and long distance runners), interestingly, the increased running endurance performance in the TG was achieved even when their BMI attained an almost significant (P=0.067) increase (Table 6). Thus, although it is possible that the TG experienced a negative modification (i.e. increased BMI), this group of endurance athletes achieved a significant increase in their running endurance performance, possible by means of adaptations induced by PT, like improved neuromuscular and anaerobic characteristics (50, 52), that in addition to VO2max, lactate threshold, among others “aerobic” indicators, may have a crucial role in the performance of endurance athletes (18, 50, 60, 106). This result agree with those of previous authors (108, 131); however, others have show that concurrent strength and endurance training did not induce significant changes in endurance performance (97-98, 109) or even had a negative effect (77). Although several limitations of these studies preclude possible generalization of their results to the training programming of highly competitive middle and long distance runners, because in these studies they had reduced the volume of endurance training by twenty percent (97-98) or even forty eight percent (109); contrasting with the current intervention where endurance training volume was not reduced. This positive concurrent strength and endurance training compatibility was possible because the total explosive-strength training time toke less that 60 min per week, which is less than 3 times the time reported in a study where reduced endurance performance was observed (77). Interference also may occur when the overall volume and/or frequency of training is higher over a longer period of time (51).

Aside from the increased running endurance performance, the TG achieved a significant increase in 20m sprint performance, whereas no significant modification was evident in CG (Table 6). Similar results have been reported previously (108, 113, 119). An increase in 20-m sprint performance have been correlated with an improved running economy, which may translate in an increased running velocity during endurance events (108). Also, the TG achieved a significant increase in explosive strength performance requiring slow SSC action (i.e. CMJA) after the intervention (no significant change was evident in the CG) (Table 6). Additionally, the study results also show that the TG achieved a significant increase in explosive-strength performance requiring fast SSC action (i.e. RSI20 and RSI40) after intervention, which, to the best of the author’s knowledge, this is the first study to investigate this in highly competitive middle- and long-distance runners (Table 6). An increased in explosive-strength performance requiring fast SSC action may reduce the time the athlete’s foot spends in contact with the ground during running (108), favorably affecting performance during running endurance events.

A significant relationship observed between initial 2.4-km time performance and relative modification in RSI40 ($r = -0.82$; $p<0.001$) suggest that athletes with the best initial running endurance performance may obtain more explosive strength adaptations trough PT, which may be an advantage for their endurance performance during running (18, 60). This finding can have important practical applications, but more studies are necessary to corroborate this result.

When the performance of athletes in the 20-m, 2.4 km, CMJA, RSI20, and RSI40 tests was standardized by means of the Z score, the TG show a significant increase, whereas the CG experienced a significant reduction. In the study, the CSP reflect not only one performance variable but include running endurance and explosive strength performance variables, both of which may have a role during competitive endurance events (18, 60), therefore, the CSP may me a convenient tool to evaluate, in a more comprehensive way, the performance state of the athlete. Also, the CSP reflect the performance of a subject in comparison with a group. Therefore, a change in CSP may reflect a change in the performance (involving several critical variables) of an athlete in comparison with their competitors. Accordingly, the study of performance through a CSP analyses may be an interesting tool to investigate competitive athletes in relation with their peers.

From a practical point of view highly competitive middle- and long-distance runners can induce both significant explosive strength adaptations and specific endurance running performance enhancements by incorporating PT in their training schedule. Subjects achieved significant adaptations with PT of short duration (i.e., 6 weeks) that toke less than 1 hour per week to be completed (i.e., low volume and moderate frequency of training). Explosive strength drills demonstrated adaptability to a specific population, integration within practice, and relative inexpensive equipment requirements (i.e., wood boxes). In fact, PT subjects (and their coaches) reported positive feelings regarding the intervention and the will to incorporate this type of training as part of their regular training program. In a follow up contact, coaches reported the inclusion of plyometric drills as part of the regular preparation of their athletes.

Concern has been expressed by some researchers with regard to the training surface used during PT due to its (speculated) high harm/injury index. To the best of the author´s knowledge, when adequate controlled PT interventions had been applied, no injuries had been reported. In fact, PT has been advocated as a preventive injury strategy (35, 76) and even as a rehabilitation tool (55). It is important to notice that in the present investigation no injuries were reported. More so, subjects reported little subjective muscle pain after the training sessions (data not shown), even when a *hard* training surface was used. Also, previous research from our group (19) had show that a reduced volume of PT, combined with a relatively hard training surface, represents an optimal stimulus to induce significant neuromuscular adaptations.

When different components of motor performance are concurrently being developed, caution must be taken so that the fatigue achieved during training one component does not adversely affect the development of the other(s). Our results showed that explosive strength and running endurance training can be completed in the same training session, which may facilitate the incorporation of this method in the training program schedule. Finally, properly programmed concurrent plyometric and running endurance training could be advantageous to middle- and long-distance runners for their competitive performance, especially in events characterized by sprinting actions with small time differences at the end of the race (57). In this regard, although our results show that the performance increment in 2.4-km time trial was significant in the TG, it is possible that a more “competitive” running endurance test (i.e., were subjects must struggle for the wining place at the ending of the race, implicating some form of sprint running) can be more representative of the “true” adaptations in competitive middle- and long-distance runners performance after a combined plyometric and endurance running combined training program. This can be considered in future researches

5.2. Study II

The main findings of this study were that high training volume led to a significant increase in explosive performance requiring fast SSC actions (i.e., RSI and sprint) compared with that observed after a moderate training volume. Second, when PT was performed on a hard training surface (high impact reaction force), a moderate training volume induced optimal stimulus to increase explosive performance requiring fast SSC actions (RSI), maximal dynamic strength, and training efficiency. Thus, an interesting finding of the study was that after 7 weeks of PT, performance enhancements in actions requiring maximal strength and fast SSC (RSI and sprint) were dependent on the training surface and training volume.

According with previous studies, jump training involving DJ exercises effectively enhanced explosive performance (58). Moreover, PT in adolescent males (similar to the one applied in this study) have shown to be effective in inducing an increase in explosive performance (135). However, in contrast with a previous study (27), the results of the present study indicate that high vs. moderate PT volume of BDJ (1,560 vs. 780 jumps in 7 weeks) led to different training-induced explosive performance gains. The MVG experienced a significant increase in SJ (18%; pre value = 27.7 ± 4.7 cm; post value = 30.0 ± 4.9 cm) (Figure 1), whereas the HVG exhibited a significant increase in RSI20 (28.8%; pre value = 0.124 ± 0.02 $cm \cdot ms^{-1}$; post value = 0.161 ± 0.02 $cm \cdot ms^{-1}$) (Figure 2) and a significant reduction in sprint time (-0.8%; pre value = 3.87 ± 0.16 seconds; post value = 3.84 ± 0.14 seconds) (Figure 3). The difference between the study results and those previously reported might be explained by the differences in the subject selection criteria. In the study of de Villarreal et al. (27), active physical education students took part in their study, whereas in this study, the subjects where recreationally young soccer players. It is worth noting the significant reduction in CMJ performance exhibited by the HVG (-4.4%; pre value = 35.1 ± 2.4 cm; post value = 33.6 ± 2.6 cm), whereas the MVG did not change their performance in this test (Figure 4). It is possible that training with high volume and low specificity (i.e., a CMJ implicates a slow SSC muscle action, whereas a BDJ implicates a fast SSC muscle action) might influence this result.

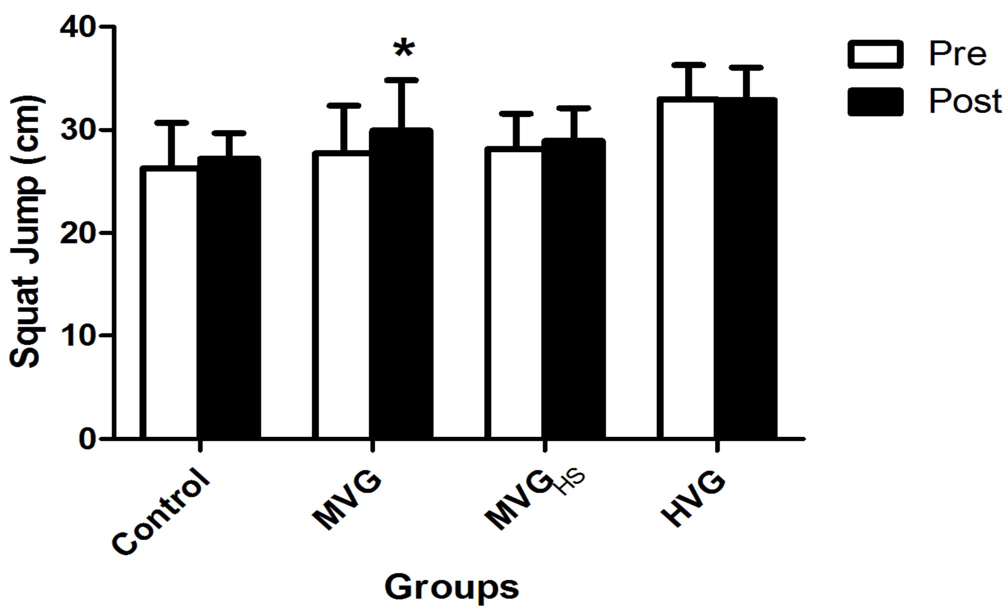


Figure 1. Squat jump (SJ) performance (cm) in experimental groups before (white columns) and after (dark columns) 7 weeks of PT in recreationally young male soccer players. MVG: moderate volume group (120 jumps per week); MVG_{HS}: moderate volume group (120 jumps per week), using hard landing surface; HVG: high volume group (240 jumps per week). * denotes significant difference with the corresponding pre value (p <0.05).

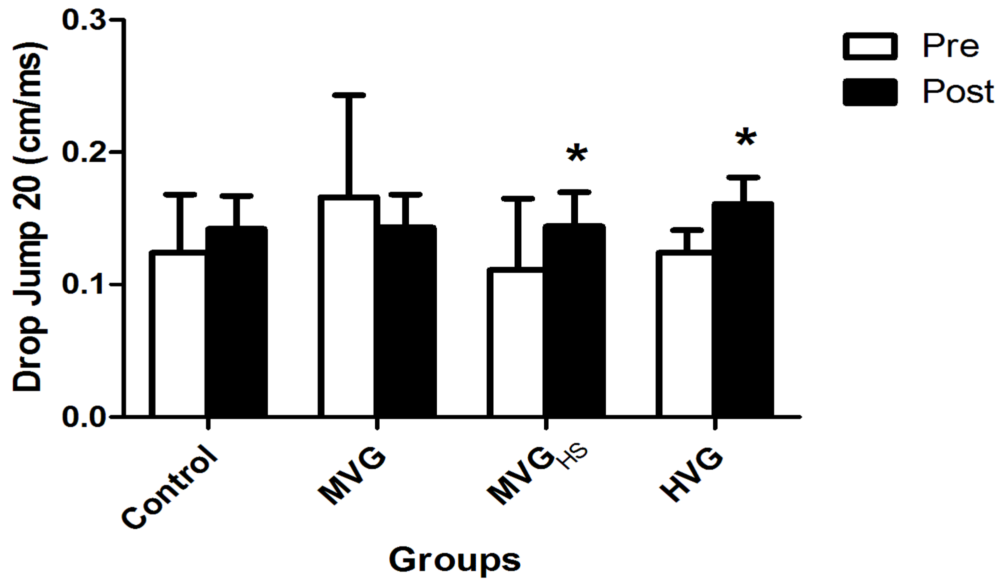


Figure 2. RSI20 performance (cm·ms^{-1}) in experimental groups before (white columns) and after (dark columns) 7 weeks of PT in recreationally young male soccer players. MVG: moderate volume group (120 jumps per week); MVG_{HS}: moderate volume group (120 jumps per week), using hard landing surface; HVG: high volume group (240 jumps per week). * denotes significant difference with the corresponding pre value (p <0.05).

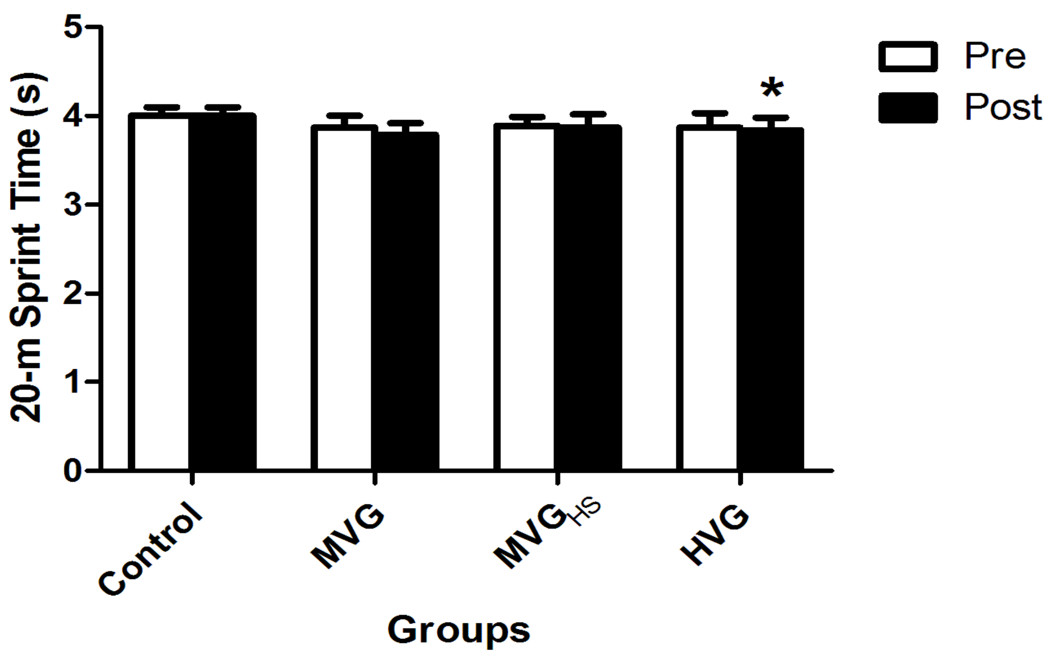


Figure 3. 20-m sprint performance (s) in experimental groups before (white columns) and after (dark columns) 7 weeks of PT in recreationally young male soccer players. MVG: moderate volume group (120 jumps per week); MVG_{HS}: moderate volume group (120 jumps per week), using hard landing surface; HVG: high volume group (240 jumps per week). * denotes significant difference with the corresponding pre value (p <0.05).

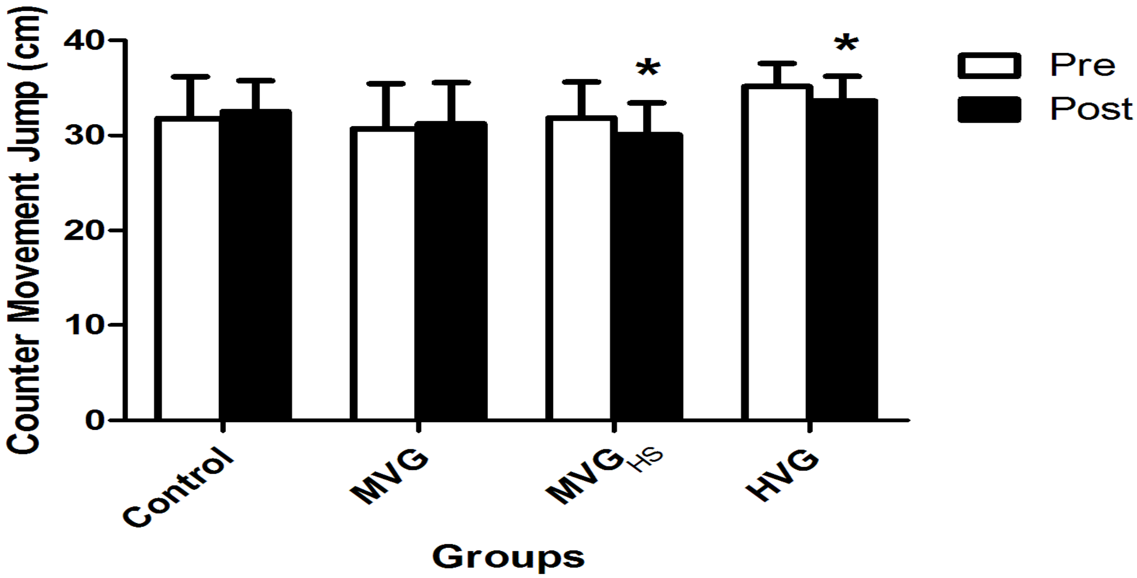


Figure 4. Counter movement jump (CMJ) performance (cm) in experimental groups before (white columns) and after (dark columns) 7 weeks of PT in recreationally young male soccer players. MVG: moderate volume group (120 jumps per week); MVG_{HS}: Moderate volume group (120 jumps per week), using hard landing surface; HVG: High volume group (240 jumps per week). * denotes significant difference with the corresponding pre value (p <0.05).

The results also show that the hardness of the training surface used during PT has an effect on training adaptations. A novel aspect of this study was to use 2 different training surfaces (gymnasium floor vs. athletic mat) for completing 7 weeks of PT and to examine their impact on jump, strength, sprint, and agility performance. Moreover, to the best of the author's knowledge, quantification on the hardness of the training surfaces for PT by means of the coefficient of restitution has not been reported before in the literature. This unique approach may establish a precedent for future PT studies. Before the intervention, MVG and MVG_{HS} exhibit similar anthropometric and performance characteristics. As mentioned before, after the intervention, the only favorable performance change exhibited by the MVG was a significant increase in SJ performance (Figure 1). On the other hand, the MVG_{HS} exhibited a significant increase in RSI20 (29.7%; pre value = 0.111 ± 0.05 $cm{\cdot}ms^{-1}$; post value = 0.144 ± 0.03 $cm{\cdot}ms^{-1}$) (Figure 2) and RSI40 (26.8%; pre value = 0.112 ± 0.04 $cm{\cdot}ms^{-1}$; post value = 0.142 ± 0.03 $cm{\cdot}ms^{-1}$) (Figure 5). The MVG_{HS} also exhibited increased performance in maximal dynamic strength (5.4%; pre value = 71.3 ± 6.9 kg; post value = 75.2 ± 5.4 kg) (Figure 6), which may be related to the increased ground impact forces encountered during landing in a hard surface. Reduction in CMJ performance by the MVG_{HS} was significant (-5.6%; pre value = 31.9 ± 3.8 cm; post value = 30.1 ± 3.3 cm) and similar to what was observed in HVG, whereas the MVG did not change this variable (Figure 4). On the other hand, a significant reduction in agility performance was observed in the MVG (-2.4%; pre value = 17.8 ± 0.7 s; post value = 18.2 ± 0.6 s) but not in the MVG_{HS} (Figure 7). The study results contrast with those reported by Stemm and Jacobson (133) that used 2 different PT surface (water vs. athletic mat) for 6 weeks. They observe no difference in performance change between the training surfaces. On the other hand, the present results agree to those reported by Impellizzeri et al. (62) in which a group of soccer players trained on 2 different surfaces (grass and sand), and reported that the soccer players trained in sand obtained a notable increase in SJ performance vs. players trained on grass.

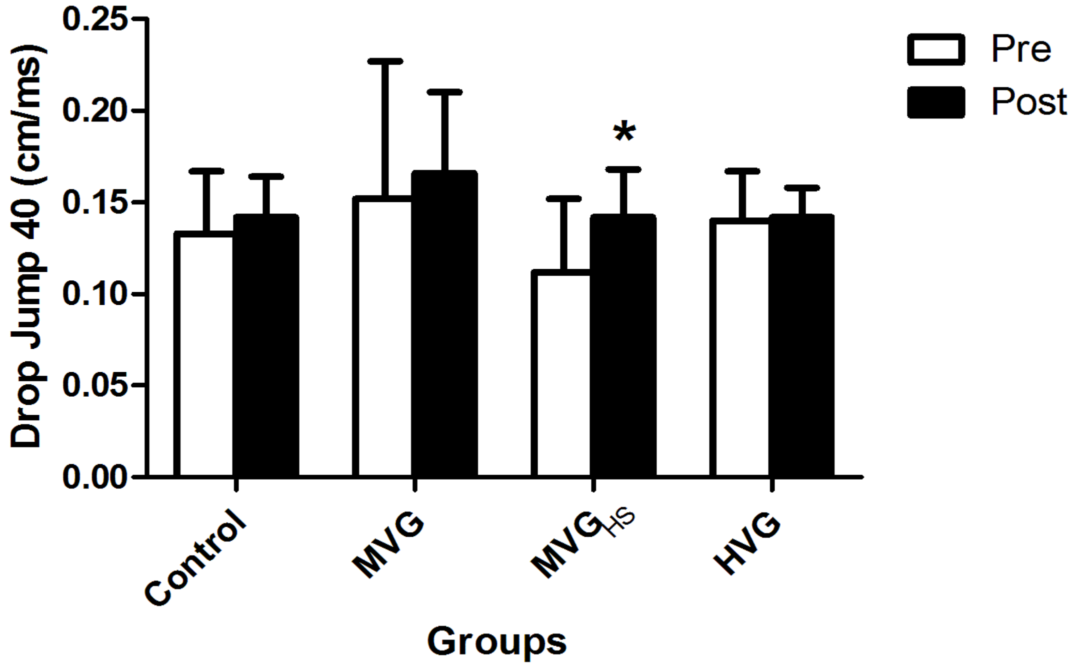


Figure 5. RSI40 performance (cm·ms^{-1}) in experimental groups before (white columns) and after (dark columns) 7 weeks of PT in recreationally young male soccer players. MVG: moderate volume group (120 jumps per week); MVG_{HS}: Moderate volume group (120 jumps per week), using hard landing surface; HVG: High volume group (240 jumps per week). * denotes significant difference with the corresponding pre value (p <0.05).

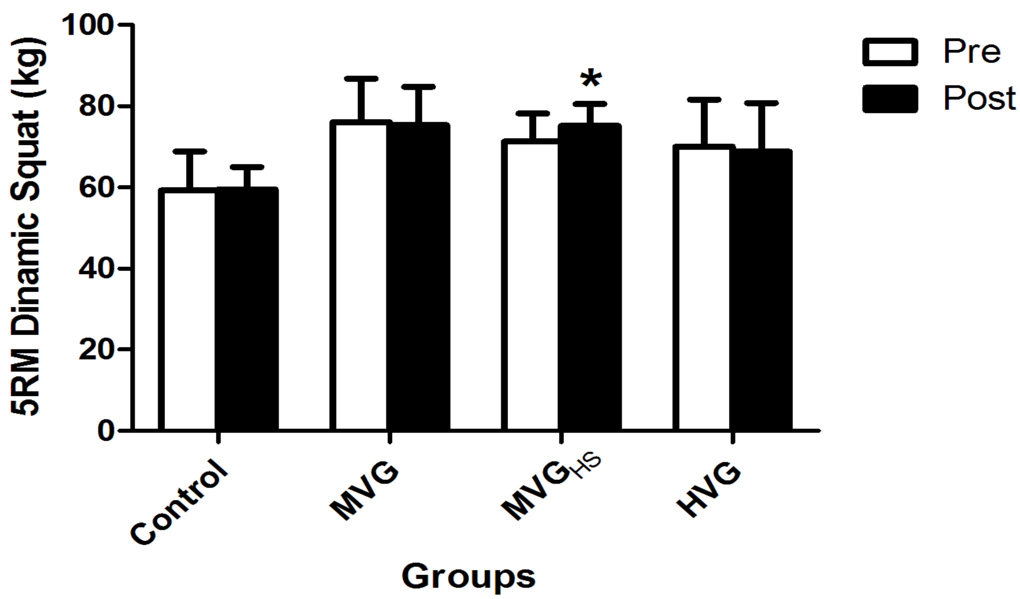


Figure 6. Maximal strength (5RM dynamic squat) performance (kg) in experimental groups before (white columns) and after (dark columns) 7 weeks of PT in recreationally young male soccer players. MVG: moderate volume group (120 jumps per week); MVG_{HS}: Moderate volume group (120 jumps per week), using hard landing surface; HVG: High volume group (240 jumps per week). * denotes significant difference with the corresponding pre value (p <0.05).

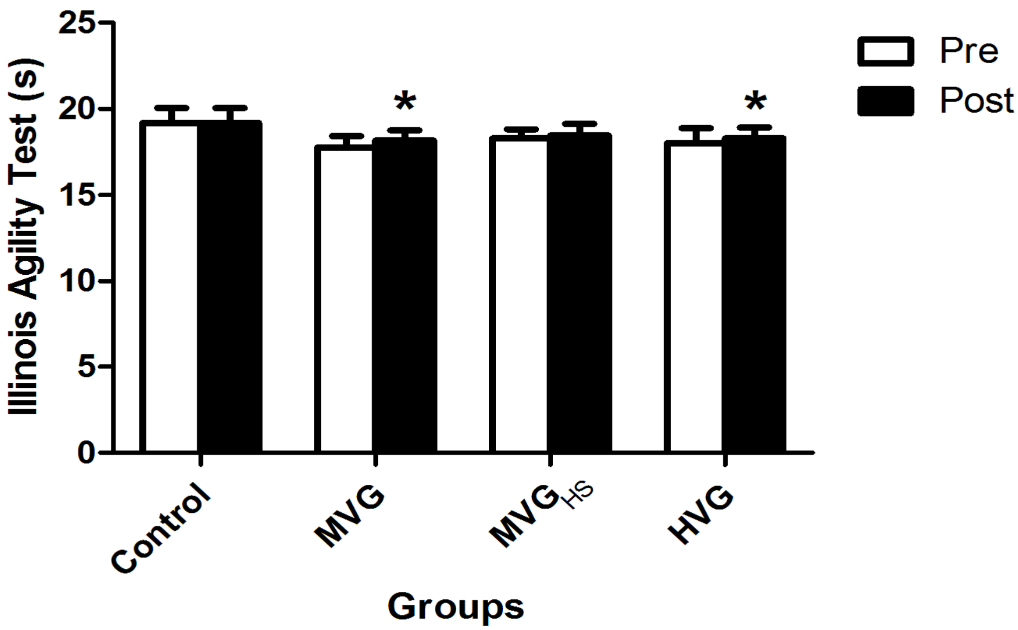


Figure 7. Agility performance (s) in experimental groups before (white columns) and after (dark columns) 7 weeks of PT in recreationally young male soccer players. MVG: moderate volume group (120 jumps per week); MVG_{HS}: Moderate volume group (120 jumps per week), using hard landing surface; HVG: High volume group (240 jumps per week). * denotes significant difference with the corresponding pre value (p <0.05).

Another interesting finding show that reduced volume of PT combined with a hard training surface, represent an optimal stimulus to induce significant neuromuscular adaptations. Therefore, the training environment (i.e., surface hardness) can be modified to increase the training efficiency of plyometric exercises. In this regard, although the MVG_{HS} and HVG show a significant and almost identical increase in explosive reactive strength during training, (29.7 and 29.8%, respectively), the training efficiency was superior in the MVG_{HS} (0.038% per jump) compared with HVG (0.019% per jump). Previous studies corroborate that a larger volume may result in less training efficiency (27, 44-45). It seems that when an optimal training load is achieved, further increases in volume do not offer additional benefits and may even negatively affect performance (44, 54, 107). The stretch loads, storage of elastic energy, pre contraction activation state, and activation of the stretch reflex can be influenced by the type of surface used during PT (10). The characteristics of a soft landing surface during PT may potentially reduce the mechanical load on the musculoskeletal system and hence the training effect on the efficiency of the muscle-tendon complex (66). This agrees with the study results, where a significant effect of training surface was found in some jump characteristics related to the efficiency of the SSC. Therefore, when a hard surface is used during PT, a low optimal volume may be indicated. On the other hand, the use of a soft landing surface during jumping may require a more intense concentric push-off phase, probably to compensate for a lower reuse of the stored elastic energy caused by the soft surface absorption (101). This may help explain why the MVG exhibited an increase in SJ performance, but still it remains unclear why the HVG training stimulus do not represent an optimal stimulus to promote similar training adaptations.

On the other hand, a relatively high volume of PT may be important to induce enhancement in sprint performance when a soft landing surface is used. In the present study, a high volume of training induced a significant reduction in sprint time (-0.8%) (Figure 3). Similar reduction has been reported previously (56). It has been speculated that the contact time during DJ exercises must be less than 200 ms to induce a specific stimuli in relation with the contact time encounter in an acceleration sprint (i.e., 20-m) (135). In the present investigation, the trained subjects were instructed to execute BDJ with emphasis on minimizing contact time and maximizing jump height. Although not controlled during training sessions, the contact time of subjects during basal evaluation (the same instruction and motivation was given during evaluation and training sessions) of BDJ executed from 20, 40, and 60 cm was almost always under 200 ms. Therefore, the specificity of the exercise (135), accompanied with a high number of repetitions, may be important to induce sprint performance enhancement, maybe by means of motor learning adaptations (80). It is important to notice that the only training group that exhibited an increase in sprint performance was the HVG. Therefore, the volume of training, not the type of surface, affected the improvement in sprint performance.

From a practical perspective, the study results indicate that different PT volumes and surfaces are associated with different explosive strength adaptations. Concretely, the data indicate that a moderate PT volume (i.e., 60 jumps per session or 120 jumps per week) would not induce an increase in sprint performance, instead, a high PT volume (i.e., 120 jumps per session or 240 jumps per week) would be necessary to induce an increase in acceleration sprint (i.e., 20-m). Therefore, a high volume of fast SSC muscle actions during training may be required to induce an increase in acceleration sprint. The study results also indicate that when moderate volume is used during PT, a hard training surface would be needed if adaptations in fast SSC muscle actions, or reactive strength, are an important objective of training. Finally, the present data also suggest that, compared to a high PT volume completed on a soft surface (i.e., 3-cm thick athletic mat), using a moderate PT volume on a hard surface (i.e., wood gymnasium floor) would double the efficiency of adaptations in reactive strength. In others words, a high volume of training would not be necessary to induce reactive strength adaptations when a hard landing surface is used. These results do not support the notion of “the more, the better.” Therefore, using a harder surface, and lower PT volume, significant (and time saving) explosive strength adaptations could be achieved.

Others important practical aspects of the study results are that, by controlling the training surface intensity, specific neuromuscular adaptations can be induced. For example, PT, with a coefficient of restitution intensity of 0.8, induced a significant increase in maximal dynamic strength, but training with a coefficient of restitution intensity of 0.53 would not be an adequate stimulus to induce increase in maximal dynamic strength. Thus, minimum threshold intensity may be required to induce neuromuscular adaptations after PT. Also, when high-intensity fast SSC muscle actions (i.e. BDJ) are performed during PT, due to their low specificity with respect to a low-moderate intensity slow SSC muscle action (i.e. CMJ), a high volume of PT, and/or a hard training surface, may negatively impact the performance during the latter type of muscle activity. Optimal design of PT programs should take these results into consideration.

5.3. Study III

The main finding in this study indicated that 7 weeks of PT induced significant and small to moderate improvements in CMJ, RSI20, RSI40, MB5, Illinois agility test time, MKD, and 2.4 km time trial performances (Table 7). These results showed that the replacement of some soccer drills with specific power training, and no additional training time in-season, optimize general and soccer-specific explosive strength adaptations in young soccer payers.

Table 7. Baseline performance measures (mean ± SD) and training effect (90% confidence limits) after the 7-week period

	Control Group		Training Group	
Variables	Baseline	Training effect (%) Effect size	Baseline	Training effect (%) Effect size
Countermovement jump (cm)	26.6 ± 4.7	2.2 (0.4, 3.9) 0.12 (0.02, 0.22)	27.0 ± 5.8	4.3[a] (3.2, 5.3) 0.20 (0.15, 0.25)
20cm reactive strength index (mm.ms^{-1})	1.01 ± 0.38	-2.7 (-6.5, 1.3) -0.07 (-0.17, 0.03)	1.04 ± 0.40	22.2[a] (17.6, 26,9[b] 0.57 (0.46, 0.68)
40cm reactive strength index (mm.ms^{-1})	1.02 ± 0.35	-2.4 (-6.7, 2.2) -0.07 (-0.2, 0.06)	1.04 ± 0.40	16.0[a] (12.5, 19.5)[b] 0.37 (0.29, 0.44)
5 multiple bounds (m)	8.71 ± 1.20	0.1 (-0.4, 0.6) 0.01 (-0.03, 0.04)	9.00 ± 1.24	4.1[a] (2.9, 5.4) 0.28 (0.19, 0.36)
20-m sprint time (s)	4.39 ± 0.48	3.7[a] (2.2, 5.2) 0.35 (0.21, 0.48)	4.32 ± 0.57	-0.4 (-1.1, 0.3) -0.03 (-0.08, 0.02)
Illinois agility test time (s)	20.1 ± 2.7	3.5[a] (2.9, 4.2) 0.25 (0.2, 0.3)	20.3 ± 2.8	-3.5[a] (-4.2, -2.8)[c] -0.26 (-0.31, -0.21)
Maximal kicking distance test (m)	30.9 ± 7.4	-1.6 (-3.0, -0.1) -0.06 (-012, 0.0)	32.7 ± 7.7	13.5[a] (10.6, 16.4)[b] 0.53 (0.42, 0.63)
2.4 km time trial (min)	10.7 ± 0.8	-0.3 (-0.8, 0.2) -0.04 (-0.10, 0.03)	10.6 ± 0.8	-1.9[a] (-2.6, -1.2) -0.27 (-0.37, -0.18)

a: denotes significant difference vs. baseline value (p<0.01); b: denotes significant difference vs. Control Group (p<0.01); c: denotes significant difference vs. Control Group (p<0.05)

The PT group significantly increased jumping performance [CMJ (+0.2 ES; 88% of responders), RSI20 (+0.57 ES; 93% of responders), RSI40 (+0.37 ES; 95% of responders), and MB5 (+0.28 ES; 81% of responders)] (Table 7). The significant improvement in jump performance in CMJ, RSI20, RSI40 and MB5 test confirms the effectiveness of the application of a BDJ-based PT stimulus in achieving explosive strength adaptations. Although we used higher rigor to include subjects in the final analyses (i.e. completion of all training session) compared to previous interventions in young subjects (44, 144), the magnitude change in CMJ and MB5 in the current study was smaller than previously reported for both the CMJ (SE = 0.50-0.87) (17, 28, 95, 149) and MB5 (SE = 0.44-0.86) (28, 95) after explosive training with young soccer players using interventions of similar duration and/or number of sessions as in the present study. However, these discrepancy in training effect can be attributed to the training specificity, as the previous studies mentioned above used both slow and fast SSC (17, 28, 95, 149) which the former being similar to CMJ, as well as horizontal stimulus (28, 95). The greater magnitude in RSI20 and RSI40 would support such contention considering the fast SCC of the current training program. In addition, Meylan and Malatesta (95), who did not include any drop jump training into their plyometric program, found no significant change in reactive strength. Considering the necessity to produce a high rate of power development in explosive actions (94), improvement in RSI may have enhance physical parameters of game performance. The improvement observed could have been induced by various neuromuscular adaptations, such as increased neural drive to the agonist muscles, improved intermuscular coordination, changes in the muscle-tendon mechanical-stiffness characteristics, changes in muscle size and/or architecture, and changes in single-fiber mechanics (89), but because no physiological measurements were made, only speculations are possibly.

A significant increase in 20-m sprint time (+0.35 ES) in the CG and no significant change in the TG (-0.03 ES; 32% of responders) (Table 7) demonstrated that a PT might be necessary during the competitive period for the acceleration ability of young soccer players. Although, the lack of improvement in 20-m sprint time after the current plyometric training demonstrated that other training stimulus may be necessary to enhance sprinting performance of young soccer players during the competitive period. A lack of improvement in sprint time after drop jump-based PT had been previously reported in young soccer players (46, 135). Acceleration has been shown to be more difficult to enhance than maximal velocity, probably because of the smaller margin for improvement and the different forces involved (25, 67). Alternatively, because the training stimulus was only vertical in nature, and according to the training principle of specificity, this may had reduced the chances for soccer players to gain adaptations (46, 123, 135) that may allow them to applied more force in the horizontal plain, which is a determining factor of horizontal sprint performance (104), specially during the acceleration phase of the sprint (114). In addition, during acceleration (i.e. 20-m sprint) it is require a relatively long contact time (95) and may be more dependent in a slower stretch-shorten cycle and rate of power production similar to the CMJ (21), which was not targeted in the current training program. Despite the lack of 20-m improvement, the TG reduced (-0.26 ES; 95% of responders) the time to complete the Illinois agility test (Table 7). The results of the study are similar to those reported previously (135) where high intensity bounce drop jumps were applied to young male soccer players and a significant increase was observed in agility performance, but not in acceleration sprint performance. It must be acknowledge that subjects from the TG complete a training program designed to induce short contact times. A reduction in contact time with PT (9, 99) may increase RSI (151), which may predict changes of direction running ability, that in conjunction with an increase in lower limb muscle power (105), reduced reaction time (148) and increased eccentric strength (126) may have contributed to this improved agility performance. Previous studies in early and pubertal soccer players have reported reduced agility test times of -3.4% (25) and -3.1% (64), similar to the result of this study (-3.5%). Contrary to the positive explosive adaptations observed in the TG, the CG exhibits a significant increase in the Illinois agility test time (Table 7). These observations reinforce the value of an independent power training program to enhance explosive actions of young soccer players.

The improvement (+0.53 ES; 70% of responders) in MKD performance (Table 7) demonstrated that soccer-specific explosive actions of young male soccer players can be enhanced during the competitive period with a short-term PT implemented as a substitute for some soccer drills. An improvement in kicking performance after PT has been previously reported in pre-adolescent (96) and adolescent soccer players (121). As players had more than a 2-year background of systematic soccer training and competition experience and given the lack of improvement in the CG, the positive change in MKD are unlikely to be related to the technical training over the short term period of 7-week in the current study. It had been suggested that an increased strength and power of legs' extensor muscles due to PT may increase kicking performance in young soccer players, and these changes could be attributed solely to neuromuscular adaptations (96). It may be that these neuromuscular adaptations had an effect on biomechanical factors related to kicking performance, such as maximum linear velocity of the toe, ankle, knee and hip at ball contact (73), resultant in higher ball kicking velocity and hence MKD.

The TG exhibited a small reduction in 2.4 km time trial (-0.27 ES; 88% of responders) (Table 7) and became significantly fitter than the CG despite no additional aerobic training. The change in neuromuscular ability in the current study, especially the RSI, is likely to be transferred into a better running economy (96, 125-126) which could potential explain the positive change in the 2.4 km time trial of the TG (108, 131). Previous explosive training in young soccer players did not induce improvement in VO_{2max} (96) or lactate thresholds (46) but was efficient at enhancing YoYo Intermittent Recovery Test Level 1 performance (149). This discrepency is likely related to the fact that change in neuromuscular power after an explosive training can contribute to the change of direction during an intermittent test (e.g. YoYo or 30-15 intermittent fitness test) with change of direction (16) or running economy (90, 131) but has a limited influence on VO_{2max} or lactate threshold (131, 138). Given the multi-directional nature of the game and necessity to cover long distances (134), explosive neuromuscular training should be considered as a complimentary method to aerobic conditioning in youth soccer players in addition to its anaerobic function.

From a practical point of view, the replacement of technical exercises with low volume-high intensity plyometric drop jump exercises was effective at improving several explosive actions and endurance capacity in youth soccer players, which may have high transference into game-play performance. Thus, a twice weekly short-term high intensity PT program, implemented as a substitute for some soccer drills within regular in-season soccer practice, can enhance explosive and endurance performance in young soccer players compared with soccer training alone. The reduced volume of plyometric training ensured minimal time allocated to non-soccer specific training while maintaining continuous physical development of young players during the season. Considering that some young soccer teams (especially amateur teams) had limited time to train (e.g. 90 min, two times per week), the current findings may be relevant to programming PT in this context. Also, during intervention, subjects reported little subjective muscle pain after the training sessions (data not shown). However, practitioners need to be mindful of the players' movement competency before introducing drop jump exercises and place a considerable emphasis on coaching. Also, in accordance to the concept of training specificity, drop jump training was most effective at improving tests replicating the training stimulus (RSI) and transferred to performance measures where vertical neuromuscular power and reactive strength were relevant (CMJ, 5MB, MKD, 2.5 km time trial). However, another or a complimentary training stimulus should be implemented to improve 20-m sprint time in young soccer players. Future studies should include training programs with multi-directional and unilateral-bilateral exercises given the nature of sprinting and other explosive movement on the field (e.g. tackling, change of direction). Finally, short-term plyometric training program can also be considered as an intervention strategy to increase kicking ability and endurance in youth soccer players, but it is recommend that this training method must be adequately incorporated in a comprehensive training program that develop the specific technical abilities critical to achieve adequate kicking performance (especially at young ages) and with an adequate aerobic conditioning program, to optimize training adaptations.

5.4. Study IV

The main finding of the study was that 7 weeks of PT, with either 30, 60 or 120 s of rest between sets of low-volume and high-intensity plyometric drills, induced significant and small to moderate similar improvements in CMJ, RSI20, RSI40, agility, and kicking test performances in young male soccer players (Table 8). Also, the study results show that the replacement of some soccer drills and specific explosive strength training with no additional training time in-season is a meaningful stimulus to enhance explosive strength adaptations in young male soccer payers.

Table 8. Anthropometrics and performance variables before and after 7 weeks of plyometric training in young soccer players

Variable	Control group (n=14)	G30 (n=13)	G60 (n=13)	G120 (n=11)
Countermovement jump (cm)				
Before	22.1 (4.9)	22.2 (4.1)	21.9 (2.1)	21.7 (4.4)
After	21.9 (4.7)	24.0 (5.6)[a]	23.9 (3.1)[a]	23.5 (5.4)[a]
Training effect (%)	-0.9 (-1.9, 1.9)	8.1 (1.3, 16.8)	9.1 (1.9, 21.9)	8.5 (1.8, 18.6)
Standardized effect	-0.1 (-0.34, 0.24)	0.49 (0.24, 0.79)*	0.58 (0.29, 0.88)*	0.55 (0.27, 0.82)*
RSI20 ($mm \cdot ms^{-1}$)				
Before	0.78 (0.2)	0.77 (0.21)	0.75 (0.2)	0.75 (0.3)
After	0.85 (0.2)	1.03 (0.2)[c]	1.01 (0.2)[c]	1.02 (0.3)[c]
Training effect (%)	8.1 (-14.4, 24.7)	33.2 (14.4, 76.1)	35.3 (15.9, 74.3)	36.6 (14.3, 81.1)
Standardized effect	0.27 (-0.31, 0.59)*	0.81 (0.38, 1.27)**	0.89 (0.48, 1.22)**	0.86 (0.39, 1.33)**
RSI40 ($mm \cdot ms^{-1}$)				
Before	0.75 (0.3)	0.74 (0.3)	0.74 (0.2)	0.73 (0.3)
After	0.84 (0.2)	1.03 (0.3)[c]	1.02 (0.3)[c]	1.06 (0.3)[c]
Training effect (%)	12.9 (-9.0, 28.7)	39.0 (8.9, 66.4)	38.9 (9.0, 65.3)	46.4 (15.4, 79.7)
Standardized effect	0.48 (-0.36, 0.72)*	0.86 (0.39, 1.6)**	0.88 (0.29, 1.41)**	0.98 (0.44, 1.51)**
20m (s)				
Before	4.3 (0.3)	4.4 (0.5)	4.3 (0.2)	4.3 (0.4)
After	4.5 (0.4)[a]	4.4 (0.3)	4.3 (0.3)	4.4 (0.4)
Training effect (%)	6.6 (2.9, 9.6)	-1.8 (-3.9, 0.7)	0.3 (-1.2, 1.9)	0.4 (-3.0, 3.3)
Standardized effect	0.65 (0.44, 1.32)**	-0.3 (-0.68, 0.28)*	0.09 (-0.19, 0.33)	0.13 (-0.33, 0.60)
Agility (s)				
Before	7.4 (0.5)	7.4 (0.6)	7.4 (0.5)	7.4 (0.7)
After	7.3 (0.4)	7.0 (0.4)[a]	7.1 (0.5)[a]	7.0 (0.6)[a]
Training effect (%)	-2.6 (-5.0, 2.5)	-6.5 (-10.9, -2.3)	-5.2 (-9.9, -1.1)	-6.9 (-12.1, -2.4)
Standardized effect	-0.4 (-0.77, 0.45)*	-1.03 (-1.42, -0.4)**	-0.87 (-1.5, -0.29)**	-1.04 (-1.6, -0.49)**
Maximal kicking distance (m)				
Before	20.0 (5.3)	19.7 (7.4)	18.9 (5.0)	19.3 (7.0)
After	20.1 (5.8)	22.0 (8.9)[a]	21.8 (4.1)[a]	21.6 (7.0)[a]
Training effect (%)	1.1 (-2.4, 6.6)	11.3 (2.3, 23.4)	15.0 (2.7, 29.9)	12.6 (4.0, 24.1)
Standardized effect	0.01 (-0.09, 0.21)	0.39 (-0.03, 0.68)*	0.49 (-0.01, 0.88)*	0.43 (0.08, 0.77)*

Before and after values are means (± SD). Training effect and standardized effect values are mean (90% confidence limits). G30, G60, and G120: 30 s, 60 s, and 120 s rest interval groups, respectively; * small standardized effect; ** moderate standardized effect; a, b, c: denote significant difference pre to post training ($p<0.05$, $p<0.01$ and $p<0.001$, respectively). RSI20 and RSI40: 20 and 40 cm drop jump reactive strength index, respectively.

Although 2 to 5 min of rest has been recommended to ensure the quality of each repetition being performed in exercise sets designed to develop muscle power (4), or even 10 min between sets of high intensity BDJ (12), and although several power-oriented studies indicate superior acute effects with long vs. short rest between training sets (2, 26, 110-111), the study results show that 30, 60, and 120 s of rest between sets of high intensity plyometric jumps ensure significant and similar adaptations during 7 weeks of training in young male soccer players. It may be argued that the PT applied represented a low training load; therefore a relatively short period of recovery between training sets to achieve performance adaptations was sufficient. However, during training players completed 60 jumps each session, including bounce drop jumps from 20, 40, and 60 cm, which can be considered high intensity exercises (aside from the maximal voluntary intensity required to complete all jumps). This load is similar to that reported in previously effective training intervention with young soccer players (135) and adolescents (19). Therefore, several possible mechanisms can be postulated to understand how a relatively short rest period between PT sets allow significant explosive performance adaptations in young male soccer players, like a reduced susceptibility to muscle damage, performance alterations, and higher ability to recover after plyometric drills (86); reduced proportion of fast twitch fibers (78); reduced relative power generation capacity related to maturation-dependent neuromotor factors (32); reduced body mass (142); greater muscle compliance (allowing rapid bone growth) (29); reduced metabolic stress associated with the short duration high velocity stretch-shortening cycle (SSC) muscle actions performed during training sets (7, 22); utilization during training of low intensity active interset and inter repetition rest to favor recovery (11); and adaptations achieved during training such as endurance capacity (149) and, hence, an improved ability to recover from high intensity exercise (136). Interestingly, it has been suggested that muscle function (i.e. jump ability, sprint performance) is probably the best indicator of muscle recovery after intense exercise, especially in athletes (29); hence, future studies in young soccer players may consider the evaluation of muscle function performance after plyometric drills with different rest times between sets to better understand the recuperation process in this population segment.

The G30, G60, and G120 groups significantly increased jumping performance in the CMJ, RSI20, and RSI40 test (Table 8), with no difference between groups. The magnitude of change in performance was similar to that previously reported in young soccer players submitted to power-oriented interventions (17, 95, 121), of similar duration and/or number of sessions as in the present study (17, 95, 121). The improvement observed, which may improve player performance, could have been induced by various neuromuscular adaptations, such as increased neural drive to the agonist muscles, improved intermuscular coordination, and/or changes in the muscle-tendon mechanical-stiffness characteristics (89); but because no physiological measurements were made, only speculations are possible.

The lack of improvement in 20-m sprint time after PT in the three experimental groups (Table 8) demonstrated that other training stimulus may be necessary to enhance sprinting performance. A lack of change in sprint time after drop jump-based PT has been previously reported in 17 years old soccer players (135). As the training stimulus was only vertical in nature, this may had reduced the chances to gain adaptations considering the importance of horizontal force production and application in sprint performance (103) and the principle of training specificity (114, 123). Despite the lack of 20-m sprint improvement, all plyometrically trained group's exhibit a significant and similar reduction to complete the agility test (Table 8). The current results are similar to those previously reported (135), where high intensity bounce drop jumps had a small positive effect on agility performance in young soccer players but only a trivial effect on 15-m sprint time. An increase in power development (105), reactive strength (151) and eccentric strength (129), may have contributed to the improvement in agility performance, while acceleration may be more dependent in a slower stretch-shorten cycle and rate of power production similar to the CMJ (21), which was not targeted in the current training program. Contrary to the positive explosive adaptations observed in the plyometrically trained groups, the CG exhibited a significant increase in their 20-m sprint test time (Table 8). These observations reinforce the value of an independent power training program to enhance explosive actions of young soccer players during their in season training.

As a novelty, the study results show that kicking performance can be similarly enhanced during the competitive period with a PT program implemented as a substitute for some soccer drills, either using 30, 60 or 120 s of rest between sets (Table 8). An improvement in kicking performance after PT has been previously reported in pre-adolescent (96) and adolescent soccer players (121). As players had more than a 2-year background of systematic soccer training and competition experience, and given the lack of improvement in the CG, the increased performance is unlikely to be related to the technical training over the short term period of 7-week. It had been suggested that an increased strength and power of legs' extensor muscles due to PT may increase kicking performance, and these changes could be attributed solely to neuromuscular adaptations (96); and these adaptations may had an effect on biomechanical factors related to kicking performance, such as maximum linear velocity of the toe, ankle, knee and hip at ball contact (73), resultant in higher ball kicking velocity and hence kicking performance.

From a practical point of view, it must be considered that the PT applied induced general (i.e. jumping, agility) and soccer-specific (i.e. kicking) explosive adaptations, which may have high transference into game-play performance. Thus, a twice weekly short-term high intensity PT program, implemented as a substitute for some soccer drills within regular in-season soccer practice, can enhance explosive performance in young soccer players compared with soccer training alone, and these improvements can be achieved using 30, 60 or 120 s of rest between plyometric sets. Considering that a shorter rest period will reduce the total training time dedicated to plyometric drills, this will give the chance to redistribute a greater amount of time to exercises needed to maximize performance in young soccer players. Also, it must be considered that although the results of the study demonstrated an increase in explosive ability after PT, it is recommend that this training method should be adequately incorporated in a comprehensive training program that develops the sport-specific abilities that are critical to achieve adequate performance, especially at young ages (early engagement hypothesis) (36), and with an adequate aerobic conditioning program to optimize training adaptations.

5.5. Study V

Despite not pair-matching individuals based on an independent variable, there were no significant differences between groups' descriptive data (Table 4). In addition, before training no significant differences were observed between groups in SJ, CMJ, RSI20, BLJ, 20-m sprint time, 10 x 5-m agility time, MST, or SR test (Table 9).

Table 9. Training effects (with 90% confidence limits) for the performance variables for the control group (CG; n = 55), plyometric training 24 h group (PT24; n = 54) and plyometric training 48 h group (PT48h; n = 57).

	Baseline Mean ± SD	Performance change (%)	Magnitude of training effect
Squat jump (cm)			
CG	31.9 ± 6.1	-1.1 (-2.1, -0.1)	-0.05 (-0.1, 0.0)
PT24	31.2 ± 6.1	4.4 (3.6, 5.2) [c]	0.22 (0.18, 0.26)*
PT48	32.8 ± 7.0	3.8 (3.3, 4.4) [c]	0.17 (0.15, 0.20)
Countermovement jump (cm)			
CG	33.1 ± 6.4	-0.4 (-1.4, 0.6)	-0.02 (-0.07, 0.03)
PT24	32.6 ± 6.1	7.4 (6.3, 8.5) [c]	0.37 (0.31, 0.42)*
PT48	34.3 ± 6.9	8.0 (6.7, 9.3) [c]	0.39 (0.33, 0.45)*
RSI20 ($mm \cdot ms^{-1}$)			
CG	1.31 ± 0.42	1.2 (-0.5, 3.0)	0.03 (-0.01, 0.08)
PT24	1.32 ± 0.40	12.2 (10.2, 14.2) [c]	0.34 (0.29, 0.39)*
PT48	1.37 ± 0.39	12.0 (10.0, 14.0) [c]	0.39 (0.33, 0.45)*
Broad long jump test (cm)			
CG	184.3 ± 29.1	-0.1 (-0.9, 0.7)	-0.01 (-0.06, 0.05)
PT24	184.1 ± 29.8	5.6 (3.4, 7.9) [c]	0.33 (0.20, 0.45)*
PT48	188.2 ± 30.0	5.3 (4.4, 6.2) [c]	0.33 (0.28, 0.39)*
20-m sprint time test (s)			
CG	4.32 ± 0.49	1.2 (0.7, 1.6)	0.10 (0.06, 0.14)
PT24	4.37 ± 0.46	-5.6 (-6.4, -4,7) [c]	-0.52 (-0.60, -0.44)*
PT48	4.26 ± 0.41	-5.1 (-5.7, -4.4) [c, d]	-0.51 (-0.57, -0.44)*
Running 10 x 5-m agility time test (s)			
CG	17.2 ± 1.1	1.8 (1.1, 2.5) [c]	0.28 (0.18, 0.38)*
PT24	17.4 ± 1.0	-3.3 (-3.8, -2.8) [c, e]	-0.63 (-0.72, -0.53)**
PT48	17.3 ± 0.9	-2.7 (-3.2, -2.3) [c, d]	-0.57 (-0.67, -0.47)*
20-m multi stage shuttle run test (min)			
CG	8.5 ± 1.8	2.4 (1.2, 3.6)	0.10 (0.05, 0.16)
PT24	8.5 ± 1.6	10.3 (8.9, 11.8) [c]	0.49 (0.43, 0.56)*
PT48	8.9 ± 1.7	10.0(8.3, 11.7) [c]	0.49 (0.41, 0.56)*
Sit and reach flexibility test (cm)			
CG	41.0 ± 4.8	-0.8 (-2.1, 0.5)	-0.07 (-0.17, 0.04)
PT24	40.3 ± 4.9	5.7 (4.4, 7.1) [c]	0.44 (0.34, 0.53)*
PT48	41.2 ± 5.2	4.7 (3.7, 5.7) [c]	0.35 (0.28, 0.42)*

[*] Small standardized effect; ** moderate standardized effect; *** large standardized effect; [a, b, c]: denote significant difference pre to post training ($p<0.05$, $p<0.01$ and $p<0.001$, respectively). [d, e]: denote significant difference with the CG post training ($p<0.05$, and $p<0.01$, respectively). Values in brackets represent 90% confidence limits. RSI20: 20 cm drop jump reactive strength index.

No significant change in the CG was observed, except for an increase in 10×5 agility test time (i.e. reduced performance), with a small clinically significant change (+0.28 SE) (Table 9). On the other hand, the 2-way variance analysis with repeated measurements (3 groups × 2 times) showed that after training both plyometrically trained groups demonstrated a statistically significant increase in SJ, CMJ, RSI20, BLJ, 20-m sprint, 10×5 agility, MST, and SR performance, with no differences between groups (Table 9). Also, the magnitudes of change analyses showed that the PT24 and PT48 groups achieve a similar small to moderate clinically significant change in SJ (+0.17; +0.22 SE), CMJ (+0.37; +0.39 SE), RSI20 (+0.34; +0.39 SE), BLJ (+0.33; +0.33 SE), 20-m sprint (-0.51; -0.52 SE), 10×5 agility (-0.57; -0.63 SE), MST (+0.49; +0.49 SE), and SR (+0.35; +0.44 SE) performance, respectively (Table 9).

Therefore, the study suggests that 6 weeks of PT, with either 24 or 48 h of rest between sessions, induced significant and small to moderate similar improvements in SJ, CMJ, RSI20, BLJ, 20-m sprint time, 10×5-m agility time, MST, and SR test performances in young male soccer players. Also, these results show that the replacement of some soccer drills with specific explosive strength training, with no additional training time in-season, is a meaningful stimulus to enhance explosive strength and endurance adaptations in young male soccer payers.

Although it has been recommended that plyometric drills should not be conducted on consecutive days in youths (30, 141), and although some interventions in young soccer players used >72 h (96, 128) or >48 h (95) of rest between plyometric training sessions *to allow for adequate recovery*, suggesting that these time frames of rest would be necessary to induce adequate training stimulation in this population of young athletes, the study shows that PT applied twice weekly in consecutive or non-consecutive days results in similar explosive and endurance adaptations in young male soccer players. It may be argued that the PT applied represented a low training load, therefore a relatively short period of recovery (i.e. <24 h) between training sessions to achieve performance adaptations was sufficient. However, from the first week of training players completed 140 jumps each session, including one legged jumps and BDJ, which can be considered high intensity exercises (aside from the maximal voluntary intensity required to complete all jumps). In addition, each training week plyometric volume was increased by 20%, and during the 6th week of training athletes completed 260 jumps during each training session, a volume similar (28) or even higher (96, 135) in comparison to the one used effectively in previous studies with young soccer players. Therefore, several possible mechanisms can be postulated to understand how this relatively short rest period between PT sessions allow significant explosive and endurance performance adaptations in the short-term when PT was applied twice weekly in young male soccer players. Some of these are: reduced susceptibility to muscle damage (compared with adults) and performance alterations, and higher ability to recover after PT (86); reduced proportion of fast twitch fibers (78); reduced relative power generation capacity related to maturation-dependent neuromotor factors (32); reduced body mass (142); greater muscle compliance (allowing rapid bone growth) (29); greater naturally anabolic-occurring processes (14); and adaptations achieved during training such as endurance capacity and, hence, an improved ability to recover from high intensity exercise (136). Future studies must be conducted to elucidate the underlying mechanism that allow young soccer players to obtain significant performance adaptations with consecutive days of PT. Interestingly, it has been suggested that muscle function (i.e. jump ability, sprint performance) is probably the best indicator of muscle recovery after intense exercise, especially in athletes (29); hence, future studies in young soccer players may consider the evaluation of muscle function performance after PT sessions with different rest times between them to better understand the recuperation process in this population segment.

The PT24 and PT48 significantly increased jumping performance (SJ, CMJ, RSI20, and BDJ), with no difference between groups (Table 9). Similar results have been reported in previous studies for SJ (28), CMJ (95), RSI (95), and horizontal jump performance (28) after PT intervention in young soccer players. The significant improvement in jump performance in SJ, CMJ, RSI20, and BDJ test confirms the effectiveness of the application of a PT stimulus in achieving explosive strength adaptations, which may improve player performance. The improvement observed could have been induced by various neuromuscular adaptations, such as increased neural drive to the agonist muscles, improved intermuscular coordination, changes in the muscle-tendon mechanical-stiffness characteristics, changes in muscle size and/or architecture, and changes in single-fiber mechanics (89); but because no physiological measurements were made, only speculations are possible.

A significant and similar decrease in 20-m sprint time in the PT24 and PT48 (Table 9) suggested that PT may be a meaningful stimulus during the competitive period for the acceleration ability of young soccer players. These results agree with those previously reported (95). The horizontal nature of the PT stimulus in these studies may help explain the increased acceleration sprint performance (123). In addition, the PT24 and PT48 significantly reduced their time to complete the running 10×5 agility test, with no differences between groups (Table 9). Previous studies in early and pubescent soccer players have reported reduced agility test times of -3.4% (25) and -3.1% (64), similar to the results of this study (-2.7% to -3.3%). It must be acknowledged that subjects from the PT24 and PT48 completed a training program with several plyometric exercises designed to induce short contact times; and a reduction in contact time with PT (99) may increase RSI, which may predict the ability to change directions while running (151). Contrary to the positive explosive adaptations observed in the PT24 and PT48, the CG exhibited a significant increase in their 10x5 agility test time (Table 9). These observations reinforce the value of an independent power training program to enhance explosive actions of young soccer players.

To the authors' knowledge, a unique finding of the present study was to report that a short-term PT program, implemented as a substitute for some soccer drills within regular in-season soccer practice, significantly enhances flexibility in young male players, and this improvement was similar in PT24 and PT48 groups (Table 9). Similarly, previous results show that young people also increase flexibility after PT (31). PT has been advocated as a preventive injury strategy for young athletes (76), and as muscle flexibility is a risk factor for developing muscle injuries in male soccer players (147), these results may have important relevance. The increased flexibility may be explained by a possible reduction of the stiffness of the muscle-tendon complex, and similar changes in the elastic behavior of adjacent joint sub-components (89).

The PT24 and PT48 groups exhibited a significant increase in endurance performance (i.e. MST), with no differences between groups. Their relative increase in endurance performance was 4 times greater than that of the CG (Table 9). The positive effects of PT on endurance performance in young soccer players has been previously reported (149). However, explosive training in young soccer players did not induce improvement in VO_{2max} (96) or lactate thresholds (46); therefore, the improvement in the MST may be related to neuromuscular power improvement useful for change of direction endurance test (16) or running economy adaptations (149). More studies must be conducted to clarify how PT influences endurance performance related to young soccer players.

From a practical point of view, it must be considered that the PT applied induced explosive and endurance adaptations, which may have high transference into game-play performance. Thus, a twice weekly short-term high intensity PT program, implemented as a substitute for some soccer drills within regular in-season soccer practice, can enhance explosive and endurance performance in young soccer players compared with soccer training alone, and these improvements can be achieved using 24 or 48 h of rest between PT sessions. Considering that some young soccer teams schedule training sessions are on consecutive days, the current findings may be relevant to programming PT in this context. Also, it is important to notice that in the present investigation, no injuries were reported. More so, subjects reported little subjective muscle pain after the training sessions (data not shown). However, it is still unknown if consecutive days of PT may have a greater risk of injury occurrence over the course of a season in comparison to a periodized plan with greater between-days rest intervals, and precaution must be taken before implementing such regime with a long term approach. In addition, it must be considered that although the results of the study demonstrated an increase in explosive and endurance ability after PT, it is recommend that this training method should be adequately incorporated in a comprehensive training program that develops the specific technical abilities that are critical to achieve adequate performance (especially at young ages), and with an adequate aerobic conditioning program to optimize training adaptations.

6. CONCLUSIONS

1. After 6 weeks of high intensity-moderate volume PT, highly competitive middle and long distance runners obtained significant running endurance and explosive-strength adaptations, and these were compatible with their regular running endurance training program (Study I).

2. During 7 weeks of BDJ-based PT, only high PT volume (240 jumps per week) induced a significant increase in sprint performance. Also, only a hard PT surface (restitution coefficient 0.8) induced an increase in maximal dynamic strength performance. Although both, a high PT volume and a hard training surface had an effect on BDJ performance, only the hard training surface induced an increase in fast SSC muscle action after high drop jump height and proves to be highly efficient to induce performance adaptations (0.038% per jump). On the other hand, a higher volume or a harder training surface may limit adaptations in maximal jump height depending on slow SSC (i.e., CMJ) or pure concentric strength (i.e., SJ) when fast SSC muscle actions are used during training (Study II).

3. An integrated low volume-high intensity vertical plyometric program within regular soccer practice can substitute some soccer drills to improve most explosive actions and endurance, but horizontal exercises should also be included to enhance sprinting performance (Study III).

4. The G30, G60 and G120 groups achieved similar improvements in explosive performance after training. Therefore, when PT sets are prescribed, 30, 60 or 120 s of rest between these is adequate to induce significant explosive adaptations in young male soccer players (Study IV).

5. The PT24 and PT48 groups achieved similar small to moderate significant improvements in explosive and endurance performance after training. Therefore, when two PT sessions are performed per week, 24 h or 48 h of rest between these is adequate to induce significant explosive and endurance adaptations in young male soccer players (Study V).

7. SUMMARY OF STUDIES

Table 10. Summary of scientific articles					
	Study 1	Study 2	Study 3	Study 4	Study 5
Groups	Experimental (n=18) Control (n=18)	Experimental 1 (n=9) Experimental 2 (n=8) Experimental 3 (n=7) Control (n=5)	Experimental (n=38) Control (n=38)	Experimental 1 (n=15) Experimental 2 (n=13) Experimental 3 (n=14) Control (n=12)	Experimental 1 (n=54) Experimental 2 (n=57) Control (n=55)
Gender	Male and Female	Male	Male	Male	Male
Mean age of groups (y)	22.1	16.9	13.2	10.1 10.4 10.4 10.3	14.2 14.1 14.0
Sport	Distance runners	Recreationally soccer players	Soccer players	Soccer players	Soccer players
Training intervention	Plyometric	Plyometric	Plyometric	Plyometric	Plyometric
Duration (weeks)	6	7	7	7	6
Frequency (days/week)	2	2	2	2	2
Exercises	3 (BDJ from 20, 40 and 60cm high boxes)	3 (BDJ from 20, 40 and 60cm high boxes)	3 (BDJ from 20, 40 and 60cm high boxes)	3 (BDJ from 20, 40 and 60cm high boxes)	13 (12 CMJA¥ + 1 BDJ)
Execution direction of exercises	Vertical	Vertical	Vertical	Vertical	Vertical-Horizontal
Laterality of exercises	Bilateral	Bilateral	Bilateral	Bilateral	Unilateral and Bilateral
Cyclic nature of exercises	Acyclic	Acyclic	Acyclic	Acyclic	Acyclic and Cyclic
Sets/exercise	2	2 2 4	2	2	2
Repetitions/set	10	10	10	10	5-10&
Rest*	48-2-15	48-1.5-5	48-1.5-15	48-0.5-15 48-1.0-15 48-2.0-15	24-2-15 48-2-15
Intensity	Maximal	Maximal	Maximal	Maximal	Maximal
Surface of training	Wood	Mat Wood Mat	Grass	Grass	Grass
PER	In season	Not applicable	In season	In season	In season
REPL	No	Not applicable	Yes	Yes	Yes
Test$^{\alpha}$	RSI20 RSI40 CMJA 20m 2.4km	5RM RSI20 RSI40 SJ CMJ 20m Agility	RSI20 RSI40 CMJA MB5 20m Agility MKD 2.4km	RSI20 RSI40 CMJ 20m Agility MKD	SJ CMJ RSI20 BLJ 20m Agility MST SR
Results¶	13 (E) 17 (E) 8.9 (E) 2.3 (E) 3.9 (E)	6 (E2) 30 (E2) 30 (E3) 27 (E2) 8.3 (E1) -5.6 (E2) -4.3 (E3) 0.8 (E3) -2.3 (E1) -1.7 (E3)	22 (E) 16 (E) 4.3 (E) 4.1 (E) -3.7 (C) 3.5 (E) -3.5 (C) 14 (E) 1.9 (E)	33.2 (E1) 35.3 (E2) 36.6 (E3) 39 (E1) 38.9 (E2) 46.4 (E3) 8.1 (E1) 9.1 (E2) 8.5 (E3) -6.6 (C) 6.5 (E1) 5.2 (E2) 6.9 (E3) 11.3 (E1) 15 (E2) 12.6 (E3)	4.4 (E1) 3.8 (E2) 7.4 (E1) 8.0 (E2) 12 (E1) 12 (E2) 5.6 (E1) 5.3 (E2) 5.6 (E1) 5.1 (E2) 3.3 (E1) 2.7 (E2) 10 (E1) 10 (E2) 5.7 (E1) 4.7 (E2)

*: denotes that values are expressed as hours-min-seconds of rest between training sessions, sets and repetitions, respectively; α: denotes that the same test were performed in the experimental and control groups; ¶: denotes that only significant results are reported, expressed as a percentage of change in performance between before and after intervention (positive values indicate a positive change in performance; negative values indicate a negative change in performance); &: denotes that the number of repetitions per set was increased in 1 each week (except for the BDJ, that always was 10 repetitions/set); ¥: denotes that 12 different CMJA exercises were performed each training session.

2.4km: 2.4 km running time trial test; 5RM: 5 repetitions maximum strength test; 20m: 20-m sprint time test; BDJ: bounce drop jumps; BLJ: broad long jump test; BW: body weight; C: control group; CMJ; countermovement jump; CMJA: countermovement jump with arms; E, E1, E2, E3: experimental groups; MB5: 5 multiple bound test; MKD: maximal kicking distance test; MST: 20-m multi-stage shuttle run test; PER: period of the training year; REPL: replacement of a portion of the usual training volume with plyometric training?; RSI20-40-60: 20-40-60 cm drop jump reactive strength index; SJ; squat Jump; SR: sit and reach test.

8. REFERENCES

1. (NCAA) NCAA. National Collegiate Athletic Association standard for testing baseball bat performance. Bat-ball coefficient of restitution. NCAA, 2009.
2. Abdessemed D, Duche P, Hautier C, Poumarat G, and Bedu M. Effect of recovery duration on muscular power and blood lactate during the bench press exercise. *Int J Sports Med* 20: 368-373, 1999.
3. Abt G, Siegler JC, Akubat I, and Castagna C. The effects of a constant sprint-to-rest ratio and recovery mode on repeated sprint performance. *J Strength Cond Res* 25: 1695-1702, 2011.
4. ACSM. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Med Sci Sports Exerc* 41: 687-708, 2009.
5. Arnason A, Sigurdsson SB, Gudmundsson A, Holme I, Engebretsen L, and Bahr R. Physical fitness, injuries, and team performance in soccer. *Med Sci Sports Exerc* 36: 278-285, 2004.
6. Aziz AR, Tan F, and Teh K. A pilot study comparing two field tests with the treadmill run test in soccer players. *J Sports Sci Med* 4: 105-112, 2005.
7. Balsom PD, Seger JY, Sjodin B, and Ekblom B. Maximal-intensity intermittent exercise: effect of recovery duration. *Int J Sports Med* 13: 528-533, 1992.
8. Ball K. Use of weighted balls for improving kicking for distance, in: *Science and Football Proceedings of the sixth World Congress on Science and Football*. R T, K F, eds. London, 2009, pp 285-289.
9. Barnes JL, Schilling BK, Falvo MJ, Weiss LW, Creasy AK, and Fry AC. Relationship of jumping and agility performance in female volleyball athletes. *J Strength Cond Res* 21: 1192-1196, 2007.
10. Bobbert MF. Drop jumping as a training method for jumping ability. *Sports Med* 9: 7-22, 1990.
11. Bogdanis GC, Nevill ME, Lakomy HK, Graham CM, and Louis G. Effects of active recovery on power output during repeated maximal sprint cycling. *Eur J Appl Physiol Occup Physiol* 74: 461-469, 1996.
12. Bompa TO. *Power training for sport: plyometrics for maximum power development.* Oakville, Ont. : Mosaic Press, 1996.
13. Bosco C, Luhtanen P, and Komi PV. A simple method for measurement of mechanical power in jumping. *Eur J Appl Physiol Occup Physiol* 50: 273-282, 1983.
14. Bouchard C and Malina RM. *Growth, maturation and physcial activity*. Champaign, IL: Human Kinetics, 1991.
15. Brughelli M, Cronin J, Levin G, and Chaouachi A. Understanding change of direction ability in sport: a review of resistance training studies. *Sports Med* 38: 1045-1063, 2008.
16. Buchheit M. The 30-15 intermittent fitness test: accuracy for individualizing interval training of young intermittent sport players. *J Strength Cond Res* 22: 365-374, 2008.
17. Buchheit M, Mendez-Villanueva A, Delhomel G, Brughelli M, and Ahmaidi S. Improving repeated sprint ability in young elite soccer players: repeated shuttle sprints vs. explosive strength training. *J Strength Cond Res* 24: 2715-2722, 2010.
18. Bulbulian R, Wilcox AR, and Darabos BL. Anaerobic contribution to distance running performance of trained cross-country athletes. *Med Sci Sports Exerc* 18: 107-113, 1986.
19. Campillo RR, Andrade DC, and Izquierdo M. Effects of plyometric training volume and training surface on explosive strength. *J Strength Cond Res*, 2012.

20. Coyle EF. Integration of the physiological factors determining endurance performance ability. *Exerc Sport Sci Rev* 23: 25-63, 1995.
21. Cronin JB and Hansen KT. Strength and power predictors of sports speed. *J Strength Cond Res* 19: 349-357, 2005.
22. Chaouachi A, Haddad M, Castagna C, Wong del P, Kaouech F, Chamari K, and Behm DG. Potentiation and recovery following low- and high-speed isokinetic contractions in boys. *Pediatr Exerc Sci* 23: 136-150, 2011.
23. Chelly MS, Fathloun M, Cherif N, Ben Amar M, Tabka Z, and Van Praagh E. Effects of a back squat training program on leg power, jump, and sprint performances in junior soccer players. *J Strength Cond Res* 23: 2241-2249, 2009.
24. Chimera NJ, Swanik KA, Swanik CB, and Straub SJ. Effects of Plyometric Training on Muscle-Activation Strategies and Performance in Female Athletes. *J Athl Train* 39: 24-31, 2004.
25. Christou M, Smilios I, Sotiropoulos K, Volaklis K, Pilianidis T, and Tokmakidis SP. Effects of resistance training on the physical capacities of adolescent soccer players. *J Strength Cond Res* 20: 783-791, 2006.
26. de Salles BF, Simao R, Miranda F, Novaes Jda S, Lemos A, and Willardson JM. Rest interval between sets in strength training. *Sports Med* 39: 765-777, 2009.
27. de Villarreal ES, Gonzalez-Badillo JJ, and Izquierdo M. Low and moderate plyometric training frequency produces greater jumping and sprinting gains compared with high frequency. *J Strength Cond Res* 22: 715-725, 2008.
28. Diallo O, Dore E, Duche P, and Van Praagh E. Effects of plyometric training followed by a reduced training programme on physical performance in prepubescent soccer players. *J Sports Med Phys Fitness* 41: 342-348, 2001.
29. Eston R, Byrne C, and Twist C. Muscle function after exercise-induced muscle damage: Considerations for athletic performance in children and adults. *J Exerc Sci Fit* 1: 85-96, 2003.
30. Faigenbaum AD. Plyometrics for kids: Facts and fallacies. *NSCA's Performance Training Journal* 5: 13-16, 2006.
31. Faigenbaum AD, McFarland JE, Keiper FB, Tevlin W, Ratamess NA, Kang J, and Hoffman JR. Effects of a short-term plyometric and resistance training program on fitness performance in boys age 12 to 15 years. *J Sports Sci Med* 6: 519-525, 2007.
32. Falk B and Dotan R. Child-adult differences in the recovery from high-intensity exercise. *Exerc Sport Sci Rev* 34: 107-112, 2006.
33. Faude O, Koch T, and Meyer T. Straight sprinting is the most frequent action in goal situations in professional football. *J Sports Sci* 30: 625-631, 2012.
34. FIFA. *Laws of the game 2012/2013.* Zurich, Switzerland: Federation Internationale de Football Association. International Football Association Board, 2012.
35. Ford KR, Myer GD, Smith RL, Byrnes RN, Dopirak SE, and Hewett TE. Use of an overhead goal alters vertical jump performance and biomechanics. *J Strength Cond Res* 19: 394-399, 2005.
36. Ford PR, Carling C, Garces M, Marques M, Miguel C, Farrant A, Stenling A, Moreno J, Le Gall F, Holmstrom S, Salmela JH, and Williams M. The developmental activities of elite soccer players aged under-16 years from Brazil, England, France, Ghana, Mexico, Portugal and Sweden. *J Sports Sci* 30: 1653-1663, 2012.

37. Foster C, Florhaug JA, Franklin J, Gottschall L, Hrovatin LA, Parker S, Doleshal P, and Dodge C. A new approach to monitoring exercise training. *J Strength Cond Res* 15: 109-115, 2001.
38. Fowler NE, Trzaskoma Z, Wit A, Iskra L, and Lees A. The effectiveness of a pendulum swing for the development of leg strength and counter-movement jump performance. *J Sports Sci* 13: 101-108, 1995.
39. Gabbett TJ, Kelly JN, and Sheppard JM. Speed, change of direction speed, and reactive agility of rugby league players. *J Strength Cond Res* 22: 174-181, 2008.
40. Garcia-Lopez D, de Paz JA, Moneo E, Jimenez-Jimenez R, Bresciani G, and Izquierdo M. Effects of short vs. long rest period between sets on elbow-flexor muscular endurance during resistance training to failure. *J Strength Cond Res* 21: 1320-1324, 2007.
41. Garcia-Pallares J and Izquierdo M. Strategies to optimize concurrent training of strength and aerobic fitness for rowing and canoeing. *Sports Med* 41: 329-343, 2011.
42. Garcia-Pallares J, Sanchez-Medina L, Carrasco L, Diaz A, and Izquierdo M. Endurance and neuromuscular changes in world-class level kayakers during a periodized training cycle. *Eur J Appl Physiol* 106: 629-638, 2009.
43. Gehri DJ, Ricard MD, Kleiner DM, and Kirkendall DT. A comparison of plyometric training techniques for improving vertical jump ability and energy production. *The Journal of Strength & Conditioning Research* 12: 85-89, 1998.
44. Gonzalez-Badillo JJ, Gorostiaga EM, Arellano R, and Izquierdo M. Moderate resistance training volume produces more favorable strength gains than high or low volumes during a short-term training cycle. *J Strength Cond Res* 19: 689-697, 2005.
45. Gonzalez-Badillo JJ, Izquierdo M, and Gorostiaga EM. Moderate volume of high relative training intensity produces greater strength gains compared with low and high volumes in competitive weightlifters. *J Strength Cond Res* 20: 73-81, 2006.
46. Gorostiaga EM, Izquierdo M, Ruesta M, Iribarren J, Gonzalez-Badillo JJ, and Ibanez J. Strength training effects on physical performance and serum hormones in young soccer players. *Eur J Appl Physiol* 91: 698-707, 2004.
47. Grant S, Aitchison T, Henderson E, Christie J, Zare S, McMurray J, and Dargie H. A comparison of the reproducibility and the sensitivity to change of visual analogue scales, Borg scales, and Likert scales in normal subjects during submaximal exercise. *Chest* 116: 1208-1217, 1999.
48. Hachana Y, Chaabene H, Nabli MA, Attia A, Moualhi J, Farhat N, and Elloumi M. Test-retest reliability, criterion related validity and minimal detectable change of the Illinois agility test in male team sport athletes. *J Strength Cond Res*, 2013.
49. Hakkinen A and Komi PV. The effect of explosive type strength training on electromyographic and force production characteristics of leg extensor muscles during concentric and various stretch-shortening cycle exercises. *Scand J Sports Sci* 7: 65-76, 1985.
50. Hakkinen K. Neuromuscular adaptation during strength training, aging, detraining, and immobilization. *Crit Rev Phys Reh Med* 6: 161-198, 1994.
51. Hakkinen K, Alen M, Kraemer WJ, Gorostiaga E, Izquierdo M, Rusko H, Mikkola J, Hakkinen A, Valkeinen H, Kaarakainen E, Romu S, Erola V, Ahtiainen J, and Paavolainen L. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *Eur J Appl Physiol* 89: 42-52, 2003.

52. Hakkinen K, Komi PV, and Alen M. Effect of explosive type strength training on isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of leg extensor muscles. *Acta Physiol Scand* 125: 587-600, 1985.
53. Hansen L, Bangsbo J, Twisk J, and Klausen K. Development of muscle strength in relation to training level and testosterone in young male soccer players. *J Appl Physiol* 87: 1141-1147, 1999.
54. Hass CJ, Garzarella L, de Hoyos D, and Pollock ML. Single versus multiple sets in long-term recreational weightlifters. *Med Sci Sports Exerc* 32: 235-242, 2000.
55. Heiderscheit BC, McLean KP, and Davies GJ. The effects of isokinetic vs. plyometric training on the shoulder internal rotators. *J Orthop Sports Phys Ther* 23: 125-133, 1996.
56. Herrero JA, Izquierdo M, Maffiuletti NA, and Garcia-Lopez J. Electromyostimulation and plyometric training effects on jumping and sprint time. *Int J Sports Med* 27: 533-539, 2006.
57. Hickson RC, Rosenkoetter MA, and Brown MM. Strength training effects on aerobic power and short-term endurance. *Med Sci Sports Exerc* 12: 336-339, 1980.
58. Holcomb WR, Lander JE, Rutland RM, and Wilson GD. The effectiveness of a modified plyometric program on power and the vertical jump. *J Strength Cond Res* 10: 89-92, 1996.
59. Hopkins WG, Marshall SW, Batterham AM, and Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 41: 3-13, 2009.
60. Houmard JA, Costill DL, Mitchell JB, Park SH, and Chenier TC. The role of anaerobic ability in middle distance running performance. *Eur J Appl Physiol Occup Physiol* 62: 40-43, 1991.
61. Ilić V, Mudrić M, Kasum G, Ćirković M, and Gavrilović D. Morphological and motor characteristics of young judokas. *Physical culture* 66: 110-118, 2012.
62. Impellizzeri FM, Rampinini E, Castagna C, Martino F, Fiorini S, and Wisloff U. Effect of plyometric training on sand versus grass on muscle soreness and jumping and sprinting ability in soccer players. *Br J Sports Med* 42: 42-46, 2008.
63. Impellizzeri FM, Rampinini E, Coutts AJ, Sassi A, and Marcora SM. Use of RPE-based training load in soccer. *Med Sci Sports Exerc* 36: 1042-1047, 2004.
64. Ingle L, Sleap M, and Tolfrey K. The effect of a complex training and detraining programme on selected strength and power variables in early pubertal boys. *J Sports Sci* 24: 987-997, 2006.
65. Itoh K, Ochi H, and Kitakoji H. Effects of tender point acupuncture on delayed onset muscle soreness (DOMS)--a pragmatic trial. *Chin Med* 3: 14, 2008.
66. Kjaer M. Role of extracellular matrix in adaptation of tendon and skeletal muscle to mechanical loading. *Physiol Rev* 84: 649-698, 2004.
67. Kotzamanidis C. Effect of plyometric training on running performance and vertical jumping in prepubertal boys. *J Strength Cond Res* 20: 441-445, 2006.
68. Kotzamanidis C, Chatzopoulos D, Michailidis C, Papaiakovou G, and Patikas D. The effect of a combined high-intensity strength and speed training program on the running and jumping ability of soccer players. *J Strength Cond Res* 19: 369-375, 2005.
69. Kraemer WJ, Noble BJ, Clark MJ, and Culver BW. Physiologic responses to heavy-resistance exercise with very short rest periods. *Int J Sports Med* 8: 247-252, 1987.
70. Kraemer WJ and Ratamess NA. Fundamentals of resistance training: progression and exercise prescription. *Med Sci Sports Exerc* 36: 674-688, 2004.

71. Kraemer WJ and Ratamess NA. Hormonal responses and adaptations to resistance exercise and training. *Sports Med* 35: 339-361, 2005.
72. le Gall F, Carling C, Williams M, and Reilly T. Anthropometric and fitness characteristics of international, professional and amateur male graduate soccer players from an elite youth academy. *J Sci Med Sport* 13: 90-95, 2010.
73. Lees A, Asai T, Andersen TB, Nunome H, and Sterzing T. The biomechanics of kicking in soccer: a review. *J Sports Sci* 28: 805-817, 2010.
74. Leger LA, Mercier D, Gadoury C, and Lambert J. The multistage 20 metre shuttle run test for aerobic fitness. *J Sports Sci* 6: 93-101, 1988.
75. Lehnert M, Lamrová I, and Elfmark M. Changes in speed and strength in female volleyball players during and after plyometric training program. *Acta Univ Palacki Olomuc Gymn* 39: 59-66, 2009.
76. Lephart SM, Abt JP, Ferris CM, Sell TC, Nagai T, Myers JB, and Irrgang JJ. Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. *Br J Sports Med* 39: 932-938, 2005.
77. Levin GT, McGuigan MR, and Laursen PB. Effect of concurrent resistance and endurance training on physiologic and performance parameters of well-trained endurance cyclists. *J Strength Cond Res* 23: 2280-2286, 2009.
78. Lexell J, Sjostrom M, Nordlund AS, and Taylor CC. Growth and development of human muscle: a quantitative morphological study of whole vastus lateralis from childhood to adult age. *Muscle Nerve* 15: 404-409, 1992.
79. Lopez-Minarro PA and Rodriguez-Garcia PL. Hamstring muscle extensibility influences the criterion-related validity of sit-and-reach and toe-touch tests. *J Strength Cond Res* 24: 1013-1018, 2010.
80. Lotze M, Braun C, Birbaumer N, Anders S, and Cohen LG. Motor learning elicited by voluntary drive. *Brain* 126: 866-872, 2003.
81. Lundin P and Berg W. A review of plyometric training. *Strength Cond J* 13: 22-30, 1991.
82. Lloyd RS, Oliver JL, Hughes MG, and Williams CA. The effects of 4-weeks of plyometric training on reactive strength index and leg stiffness in male youths. *J Strength Cond Res* 26: 2812-2819, 2012.
83. MacDougall JD, Sale DG, Moroz JR, Elder GC, Sutton JR, and Howald H. Mitochondrial volume density in human skeletal muscle following heavy resistance training. *Med Sci Sports* 11: 164-166, 1979.
84. Maio Alves JM, Rebelo AN, Abrantes C, and Sampaio J. Short-term effects of complex and contrast training in soccer players' vertical jump, sprint, and agility abilities. *J Strength Cond Res* 24: 936-941, 2010.
85. Marginson V and Eston R. The relationship between torque and joint angle during knee extension in boys and men. *J Sports Sci* 19: 875-880, 2001.
86. Marginson V, Rowlands AV, Gleeson NP, and Eston RG. Comparison of the symptoms of exercise-induced muscle damage after an initial and repeated bout of plyometric exercise in men and boys. *J Appl Physiol* 99: 1174-1181, 2005.
87. Markovic G. Does plyometric training improve vertical jump height? A meta-analytical review. *Br J Sports Med* 41: 349-355; discussion 355, 2007.
88. Markovic G, Dizdar D, and Jaric S. Evaluation of tests of maximum kicking performance. *J Sports Med Phys Fitness* 46: 215-220, 2006.
89. Markovic G and Mikulic P. Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Med* 40: 859-895, 2010.

90. Marta C, Marinho DA, Barbosa TM, Izquierdo M, and Marques MC. Effects of concurrent training on explosive strength and VO2max in prepubescent children. *Int J Sports Med*, 2013.
91. McClenton LS, Brown LE, Coburn JW, and Kersey RD. The effect of short-term VertiMax vs. depth jump training on vertical jump performance. *J Strength Cond Res* 22: 321-325, 2008.
92. McGinnis M. *Biomechanics of Sport and Exercise*. Champaign, IL: Human Kinetics, 2002.
93. Mero A, Komi PV, and Gregor RJ. Biomechanics of sprint running. A review. *Sports Med* 13: 376-392, 1992.
94. Meylan C, Cronin J, Manson S, Oliver J, and Hughes M. An integrative model of power development in youth football. *Int J Sports Sci Coach*, In Press.
95. Meylan C and Malatesta D. Effects of in-season plyometric training within soccer practice on explosive actions of young players. *J Strength Cond Res* 23: 2605-2613, 2009.
96. Michailidis Y, Fatouros IG, Primpa E, Michailidis C, Avloniti A, Chatzinikolaou A, Barbero-Alvarez JC, Tsoukas D, Douroudos, II, Draganidis D, Leontsini D, Margonis K, Berberidou F, and Kambas A. Plyometrics' trainability in preadolescent soccer athletes. *J Strength Cond Res* 27: 38-49, 2013.
97. Mikkola J, Rusko H, Nummela A, Pollari T, and Hakkinen K. Concurrent endurance and explosive type strength training improves neuromuscular and anaerobic characteristics in young distance runners. *Int J Sports Med* 28: 602-611, 2007.
98. Mikkola JS, Rusko HK, Nummela AT, Paavolainen LM, and Hakkinen K. Concurrent endurance and explosive type strength training increases activation and fast force production of leg extensor muscles in endurance athletes. *J Strength Cond Res* 21: 613-620, 2007.
99. Miller MG, Herniman JJ, Ricard MD, Cheatham CC, and Michael TJ. The effects of a 6-week plyometric training program on agility. *J Sport Sci Med* 5: 459-465, 2006.
100. Mirkov D, Nedeljkovic A, Kukolj M, Ugarkovic D, and Jaric S. Evaluation of the reliability of soccer-specific field tests. *J Strength Cond Res* 22: 1046-1050, 2008.
101. Miyama M and Nosaka K. Influence of surface on muscle damage and soreness induced by consecutive drop jumps. *Journal of Strength and Conditioning Research* 18: 206-211, 2004.
102. Moir G, Button C, Glaister M, and Stone MH. Influence of familiarization on the reliability of vertical jump and acceleration sprinting performance in physically active men. *Journal of Strength and Conditioning Research* 18: 276-280, 2004.
103. Morin JB, Bourdin M, Edouard P, Peyrot N, Samozino P, and Lacour JR. Mechanical determinants of 100-m sprint running performance. *Eur J Appl Physiol* 112: 3921-3930, 2012.
104. Morin JB, Edouard P, and Samozino P. Technical ability of force application as a determinant factor of sprint performance. *Med Sci Sports Exerc* 43: 1680-1688, 2011.
105. Negrete R and Brophy J. The relationship between isokinetic open and closed chain lower extremity strength and functional performance. *J Sport Rehabil* 9: 46-61, 2000.
106. Noakes TD. Implications of exercise testing for prediction of athletic performance: a contemporary perspective. *Med Sci Sports Exerc* 20: 319-330, 1988.
107. Ostrowski KJ, Wilson GJ, Weatherby R, Murphy PW, and Lyttle AD. The effect of weight training volume on hormonal output and muscular size and function. *Journal of Strength and Conditioning Research* 11: 148-154, 1997.

108. Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, and Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol* 86: 1527-1533, 1999.
109. Paavolainen L, Hakkinen K, and Rusko H. Effects of explosive type strength training on physical performance characteristics in cross-country skiers. *Eur J Appl Physiol Occup Physiol* 62: 251-255, 1991.
110. Pincivero DM, Gear WS, Moyna NM, and Robertson RJ. The effects of rest interval on quadriceps torque and perceived exertion in healthy males. *J Sports Med Phys Fitness* 39: 294-299, 1999.
111. Pincivero DM, Lephart SM, and Karunakara RG. Effects of Intrasession Rest Interval on Strength Recovery and Reliability During High Intensity Exercise. *The Journal of Strength & Conditioning Research* 12: 152-156, 1998.
112. Polhemus R and Burkhardt ET. The effects of plyometric training drills on the physical strength gains of collegiate football players. *NSCA Journal* 2: 14-17, 1980.
113. Rahimi R, Behpur, N. The effects of plyometric, weight and plyometric-weight training on anaerobic power and muscular strength. *Facta Univ Phys Educ Sport* 3: 81-91, 2005.
114. Randell AD, Cronin JB, Keogh JW, and Gill ND. Transference of Strength and Power Adaptation to Sports Performance-Horizontal and Vertical Force Production. *Strength Cond J* 32: 100-106, 2010.
115. Ratel S, Duche P, and Williams CA. Muscle fatigue during high-intensity exercise in children. *Sports Med* 36: 1031-1065, 2006.
116. Ratel S, Lazaar N, Williams CA, Bedu M, and Duche P. Age differences in human skeletal muscle fatigue during high-intensity intermittent exercise. *Acta Paediatr* 92: 1248-1254, 2003.
117. Read MM and Cisar C. The influence of varied rest interval lengths on depth jump performance. *Journal of Strength and Conditioning Research* 15: 279-283, 2001.
118. Reilly T, Bangsbo J, and Franks A. Anthropometric and physiological predispositions for elite soccer. *J Sports Sci* 18: 669-683, 2000.
119. Robinson LE, Devor ST, Merrick MA, and Buckworth J. The effects of land vs. aquatic plyometrics on power, torque, velocity, and muscle soreness in women. *J Strength Cond Res* 18: 84-91, 2004.
120. Ronnestad BR, Kvamme NH, Sunde A, and Raastad T. Short-term effects of strength and plyometric training on sprint and jump performance in professional soccer players. *J Strength Cond Res* 22: 773-780, 2008.
121. Rubley MD, Haase AC, Holcomb WR, Girouard TJ, and Tandy RD. The effect of plyometric training on power and kicking distance in female adolescent soccer players. *J Strength Cond Res* 25: 129-134, 2011.
122. Saez-Saez de Villarreal E, Requena B, and Newton RU. Does plyometric training improve strength performance? A meta-analysis. *J Sci Med Sport* 13: 513-522, 2010.
123. Saez de Villarreal E, Requena B, and Cronin JB. The effects of plyometric training on sprint performance: a meta-analysis. *J Strength Cond Res* 26: 575-584, 2012.
124. Saraslanidis P, Petridou A, Bogdanis GC, Galanis N, Tsalis G, Kellis S, and Mougios V. Muscle metabolism and performance improvement after two training programmes of sprint running differing in rest interval duration. *J Sports Sci* 29: 1167-1174, 2011.
125. Saunders PU, Pyne DB, Telford RD, and Hawley JA. Factors affecting running economy in trained distance runners. *Sports Med* 34: 465-485, 2004.

126. Saunders PU, Telford RD, Pyne DB, Peltola EM, Cunningham RB, Gore CJ, and Hawley JA. Short-term plyometric training improves running economy in highly trained middle and long distance runners. *J Strength Cond Res* 20: 947-954, 2006.
127. Shah S. Plyometric exercises. *Int J Health Sci Res* 2: 115-126, 2012.
128. Shalfawi S IJ, Dillern T, Tønnessen E, Delp T, Enoksen E. The effect of 40 m repeated sprint training on physical performance in young elite male soccer players. *Serb J Sports Sci* 6: 111-116, 2012.
129. Sheppard JM and Young WB. Agility literature review: Classifications, training and testing. *J Sport Sci* 24: 919-932, 2006.
130. Sinnett AM, Berg K, Latin RW, and Noble JM. The relationship between field tests of anaerobic power and 10-km run performance. *J Strength Cond Res* 15: 405-412, 2001.
131. Spurrs RW, Murphy AJ, and Watsford ML. The effect of plyometric training on distance running performance. *Eur J Appl Physiol* 89: 1-7, 2003.
132. Steben RE and Steben AH. The validity of the stretch shortening cycle in selected jumping events. *J Sports Med Phys Fitness* 21: 28-37, 1981.
133. Stemm JD and Jacobson BH. Comparison of land- and aquatic-based plyometric training on vertical jump performance. *Journal of Strength and Conditioning Research* 21: 568-571, 2007.
134. Stolen T, Chamari K, Castagna C, and Wisloff U. Physiology of soccer: an update. *Sports Med* 35: 501-536, 2005.
135. Thomas K, French D, and Hayes PR. The effect of two plyometric training techniques on muscular power and agility in youth soccer players. *Journal of Strength and Conditioning Research* 23: 332-335, 2009.
136. Tomlin DL and Wenger HA. The relationship between aerobic fitness and recovery from high intensity intermittent exercise. *Sports Med* 31: 1-11, 2001.
137. Tonnessen E, Shalfawi SA, Haugen T, and Enoksen E. The effect of 40-m repeated sprint training on maximum sprinting speed, repeated sprint speed endurance, vertical jump, and aerobic capacity in young elite male soccer players. *J Strength Cond Res* 25: 2364-2370, 2011.
138. Turner AM, Owings M, and Schwane JA. Improvement in running economy after 6 weeks of plyometric training. *J Strength Cond Res* 17: 60-67, 2003.
139. Vaczi M. Contributing variables to depth jump performance. Memphis: University of Memphis, 2000.
140. Vaeyens R, Malina RM, Janssens M, Van Renterghem B, Bourgois J, Vrijens J, and Philippaerts RM. A multidisciplinary selection model for youth soccer: the Ghent Youth Soccer Project. *Br J Sports Med* 40: 928-934; discussion 934, 2006.
141. Wathen D. Literature review: explosive/plyometric exercises. *Strength & Conditioning Journal* 15: 17-19, 1993.
142. Webber LM, Byrnes BC, Rowland TW, and Foster VL. Serum creatine kinase activity and delayed onset muscle soreness in prepubescent children: a preliminary study. *Ped Exer Sc* 1, 1989.
143. Weeks BK and Beck BR. The relationship between physical activity and bone during adolescence differs according to sex and biological maturity. *J Osteoporos* 2010: 546593, 2010.
144. Weeks BK, Young CM, and Beck BR. Eight months of regular in-school jumping improves indices of bone strength in adolescent boys and Girls: the POWER PE study. *J Bone Miner Res* 23: 1002-1011, 2008.

145. Weyand PG and Davis JA. Running performance has a structural basis. *J Exp Biol* 208: 2625-2631, 2005.
146. Wilson GJ, Newton RU, Murphy AJ, and Humphries BJ. The optimal training load for the development of dynamic athletic performance. *Med Sci Sports Exerc* 25: 1279-1286, 1993.
147. Witvrouw E, Danneels L, Asselman P, D'Have T, and Cambier D. Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. A prospective study. *Am J Sports Med* 31: 41-46, 2003.
148. Wojtys EM, Huston LJ, Taylor PD, and Bastian SD. Neuromuscular adaptations in isokinetic, isotonic, and agility training programs. *Am J Sports Med* 24: 187-192, 1996.
149. Wong PL, Chamari K, and Wisloff U. Effects of 12-week on-field combined strength and power training on physical performance among U-14 young soccer players. *J Strength Cond Res* 24: 644-652, 2010.
150. Yamamoto LM, Lopez RM, Klau JF, Casa DJ, Kraemer WJ, and Maresh CM. The effects of resistance training on endurance distance running performance among highly trained runners: a systematic review. *J Strength Cond Res* 22: 2036-2044, 2008.
151. Young WB, James R, and Montgomery I. Is muscle power related to running speed with changes of direction? *J Sports Med Phys Fitness* 42: 282-288, 2002.

9. LIST OF SCIENTIFIC ARTICLES

Study I. Ramírez-Campillo R, Álvarez C, Henríquez-Olguín C, Báez-San Martín E, Martínez C, Andrade DC, Izquierdo M (2013). Effects of plyometric training on endurance and explosive-strength performance in competitive middle and long distance runners. J Strength Cond Res DOI: 10.1519/JSC.0b013e3182a1f44c (Impact Factor: 1.831, Journal ranking: 2nd Quartile; Sports Sciences).

Este artículo ha sido eliminado por restricciones de derechos de autor

Study II. Ramírez-Campillo R, Andrade DC, Izquierdo, M. (2013). Effects of plyometric training volume and training surface on explosive strength. J Strength Cond Res. DOI: 10.1519/JSC.0b013e318280c9e9 (Impact Factor: 1.831, Journal ranking: 2nd Quartile; Sports Sciences).

Este artículo ha sido eliminado por restricciones de derechos de autor

Study III. Ramírez-Campillo R, Meylan C, Álvarez C, Henríquez-Olguín C, Martínez C, Cañas-Jamet R, Andrade DC, Izquierdo M (2013). Effects of in-season low volume-high intensity plyometric training on explosive actions and endurance of young soccer players. J Strength Cond Res. Epub ahead of print (Impact Factor: 1.831, Journal ranking: 2nd Quartile; Sports Sciences).

Este artículo ha sido eliminado por restricciones de derechos de autor

ABSTRACT

Integrating specific training methods to improve explosive actions and endurance in youth soccer is an essential part of players' development. The current study investigated the efficiency of short-term vertical plyometric training program within soccer practice to improve both explosive actions and endurance in young soccer players. Seventy-six players were recruited and assigned either to a training (TG; n = 38; 13.2±1.8 y) or control (CG; n = 38; 13.2±1.8 y) group. All players trained twice per week but the TG followed a 7-week plyometric program implemented within soccer practice while the CG followed regular practice. Twenty-meter sprint time (20-m), Illinois agility test time, countermovement jump height (CMJ), 20 (RSI20) and 40 (RSI40) cm drop jump reactive strength index, multiple 5 bounds distance (MB5), kicking distance (MKD) and 2.4 km time trial were measured prior and after the 7-week period. Plyometric training induced significant ($P < 0.05$) and small to moderate standardized effect (SE) improvement in the CMJ (4.3%; SE = 0.20), RSI20 (22%; SE = 0.57), RSI40 (16%; SE = 0.37), MB5 (4.1%; SE = 0.28), Illinois agility test time (-3.5%, SE = -0.26), MKD (14%; SE = 0.53), 2.4 km time trial (-1.9%; SE = -0.27) performances, but had a trivial and non-significant effect on 20-m (-0.4%; SE = -0.03). No significant improvements were found in the CG. An integrated vertical plyometric program within regular soccer practice can substitute some soccer drills to improve most explosive actions and endurance, but horizontal exercises should also be included to enhance sprinting performance.

KEY WORDS: agility, explosive-strength, stretch-shortening cycle, vertical jump.

INTRODUCTION

Soccer is an intermittent sport which requires different physiological components. The capacity to produce varied powerful actions during a 90-minute game is associated with high aerobic capacity (41). However, the ability to produce an explosive single-bout effort is as important as aerobic power for success in soccer (9). This includes movements such as sprinting, jumping, changing direction, throwing or kicking frequently occurring in soccer (41). Many of these activities not only require maximal power but also a high rate of power development considering the short period spent on the ground to produce power, such as sprinting or changing direction (< 100 ms) (1, 26). Various studies demonstrated that youth elite and/or sub-elite players were found to be faster, more agile and more powerful than non-elite (16, 45), while, future international and professional players had superior explosive characteristics (i.e. speed, power) at youth level than future amateur players (20). These results support the fact that soccer-related, explosive activities requiring power may not only be important qualities at youth level (16, 45) but also at a later stage of a player's career (20) and need to be developed from a young age.

Plyometric exercises are commonly used to increase explosive actions in pubertal (42) and prepubertal (8, 28-29) soccer players, with the advantage of being easy to integrate in soccer practice (space, time, equipment), and replicating the neuromuscular stimulus encountered in explosive soccer activities such as sprinting and jumping (12). Previous studies demonstrated that high intensity plyometric exercises, such as drop jumps, can be used safely and effectively, from the beginning of training in young population (4) and soccer players (42). Generally, the high intensity requirements of drop jump training implies a reduced volume in training (4, 7) and therefore may require less time to complete than other plyometric modes, while inducing comparable training adaptations to slow SCC training (42). The ability to continue improving explosive action during in-season is a challenge due to the limited time available for isolated training when the emphasis is mostly placed on technical development in youth soccer (27). Meylan et and Malatesta (28) demonstrated that in-season high volume plyometric training (~100-120 ground contact/session) can increase explosive performance but it remains unknown if a low volume high intensity training may induce similar changes in sprinting, jumping and change of direction. Such approach may appear relevant to the time constraint that coaches may encounter for both physical and technical development of players.

Apart from sprinting, jumping and change of direction, explosive training may also be beneficial to other soccer specific athletic requirements such as ball kicking or endurance. Previous studies (29, 48) investigating kicking velocity or distance demonstrated the efficiency of explosive training to improve this quality, but improvement in aerobic performance remained controversial. Some studies in exposive training in youth soccer players did not demonstrate any improvement in VO_{2max} (29) or lactate thresholds (14), while others (48) demonstrated the efficicency of explosive training to improve YoYo intermittent recovery test and submaximal running cost. Similary, research in adult runners demonstrated that plyometric training may improve running time trial and economy but not VO_{2max} and lactate threshold (32, 40, 44). It is therefore of interest to identify if plyometric in youth players have a positive influence on middle distance running time trial, considering its mulitple facet requirement (VO_{2max}, lactate threshold and running economy) (32), likely to affect aerobic performance in soccer (41).

Given the limitations of the current literature, the purpose of this study was to determine the effect of replacing some soccer drills with low-volume high-intensity plyometric training exercises, on explosive actions and middle distance time trial of young soccer players during in-season. It was hypothesized that the replacement of some soccer drills with plyometric exercises, with no additional training time in-season, would enhance explosive actions and aerobic performance to a greater extent than soccer training alone.

METHODS

Experimental Approach to the Problem

We examined the ability of an in-season short-term plyometric training program, implemented as a substitute for some soccer drills within regular soccer practice, to improve physical performance compared to soccer practice alone. Two groups were formed from young male soccer players; one followed the modified soccer practice (training group, TG) and the other followed the regular soccer practice (control group, CG). Before and after a 7-week period, all players executed a battery of 8 tests related to explosive and endurance performance. This was a randomized controlled trial. The assigned groups were determined by a chance process (a random number generator on a computer) and could not be predicted. This procedure was established according to the "CONSORT" statement, which can be found at: http://www.consort-statement.org.

Subjects

Initially 121 male soccer players between 10 and 16 years of age fulfill the inclusion criteria to participate in the study. Subjects were recruited from 4 different soccer teams with similar competitive schedule (one official competitive game per week) and soccer drills used during their two weekly training sessions. Soccer players full-filled the following inclusion criteria: 1) more than 2-year background of systematic soccer training and competition experience; 2) continuous soccer training in the last 6 months, 3) no plyometric training experience in the last 6 months, 4) no background in regular strength training or competitive sports activity that involved any kind of jumping training exercise during the treatment. To be included in the final analyses participants were required to complete all the familiarization sessions, training sessions and complete all tests, which resulted in 76 players included for the final analyses. Subjects were randomly divided into a control group (CG; N=38) and plyometric training group (TG; N=38). Subject characteristics are provided in Table 1. Institutional Review Board approval for our study was obtained, and all subjects (and their parents or guardians) were carefully informed about the experiment procedures, and about the possible risk and benefits associated with participation in the study, and an appropriate signed informed consent/assent document has been obtained pursuant to law before any of the tests were performed. We comply with the human and animal experimentation policy statements guidelines of the American College of Sport Medicine. Sample size was computed according to changes observed in plyometric (i.e., reactive strength index) performance (d = 0.3 mm/ms; SD = 0.35) in a group of young adolescents submitted to the same training program applied in this study (4). A total of 8 participants per group would yield a power of 80% and a = 0.05.

******Insert Table 1 near here******

Testing Procedures

Subjects followed a familiarization session of 90 min prior to testing to reduce any learning effects. Standardized tests were scheduled >48 hours following a competition or hard physical training to minimize the influence of fatigue and performed under similar weather, time and field conditions before and immediately after the 7-week period over two days. On day one, players characteristics (height, body mass and self-assessed Tanner pubic hair and genital stage) and performance test were conducted in the following order: countermovement jump (CMJ), 20 (RSI20) and 40 (RSI40) cm drop jump reactive strength index, five alternated leg bounds test (MB5), 20-m sprint (20m), and Illinois agility test. On day two, maximal kicking test for distance

(MKD) followed by a 2.4 km time trial were performed. All tests were administered in the same order pre- and post-training in the same sporting clothes and recorded by the same investigators. In addition, all participants (and their parents or guardians) were instructed to have a good night's sleep (≥9 h) before each testing day, to avoid drinking or eating at least 2-3 h before measurements. All participants were motivated to give their maximum effort during performance measurements. At least two minutes of rest was allowed between each trial to reduce fatigue effects. While waiting, participants performed low-intensity activity to maintain physiological readiness for the next test. The best score of three trials was recorded for all performance tests apart for the single 2.4 km time trial. As in previous studies from our laboratory (4) high intraclass correlation coefficients were obtained for the different performance test, varying between 0.81 to 0.98.

Subject characteristics. Height was measured using a wall-mounted stadiometer (Butterfly, Shanghai, China) recorded to the nearest 0.5 centimeter, body mass was measured to the nearest 0.1 kg using a digital scale (BC-554 Ironman Body Composition Monitor, Tanita, Illinois, USA) and body mass index (BMI) was calculated (kg/m^2). Maturity was determined by self-assessment of Tanner stage (46).

Vertical Jump Tests. Testing included the execution of maximal CMJ, RSI20 and RSI40. All jumps were performed on a mobile contact mat (Ergojump, Globus, Codogne, Italy) with arms akimbo. Take-off and landing was standardized to full knee and ankle extension on the same spot. The participants were instructed to maximize jump height and minimize ground contact time during the RSI20 and RSI40 after dropping down from a 20 cm and 40 cm drop box, respectively. The RSI variable was calculated as previously reported (49).

Multiple 5 Bounds Test. The multiple 5 bounds test (MB5) was started from a standing position and performed a set of 5 forward jumps with alternative left- and right-leg contacts to cover the longest distance possible. The distance of the MB5 was measured to the nearest 0.5 cm using a tape measure (28).

20-m sprint and Illinois agility test. The sprint time was measured to the nearest 0.01 s using single beam infrared reds photoelectric cells (Globus Italia, Codogne, Italy). The starting position was standardized to a still split standing position with the toe of the preferred foot forward and behind the starting line. Sprint start was given by a random sound which triggers timing. The photoelectectric signal was positioned at 20 m and set approximately 0.7 m above the floor (i.e. hip level) to capture the trunk movement rather than a false trigger from a limb. The Illinois agility test has been described and its reliability addressed elsewhere (15). The timing system and procedures were the same as the 20-m sprint, except that subjects started lying on their stomach on the floor with their face down.

Maximal kicking distance test. After a standard warm-up, each player kicked a new size five soccer ball (Nike Seitiro, FIFA certified) (10) for maximal distance on a soccer field. Two markers were placed on the ground side by side to define the kick line. Participants performed a maximal instep kick with their dominant leg after a run up of two strides. A 75 m metric tape was placed between the kicking line and across the soccer field. An assessor was placed near the region where the ball land after the kick to mark the point of contact and to measure the distance kicked. The distance was measured to the nearest 0.2 m. All measurements were completed with a wind velocity <20 km/h (Chilean Meteorological Service, Santiago, Chile). Previous studies have reported a high reliability of similar soccer kicking test (23).

2.4 km time trial. After a warm-up of two laps and 4 min rest, players performed six laps of a 400 m outdoor dirt track timed to the nearest second using a stopwatch. The wind velocity at all times was less than 9.9 km/h, the relative humidity was between 50-70%, and the temperature was between 15-20°C (Chilean Meteorological Service, Santiago, Chile). Motivation was considered maximal as this test was conducted as part of selection process.

Training Program

The study was completed during the mid-portion of their competition period. Previous to the competitive period subjects completed two months of summer pre season training. The control group did not perform the plyometric training, but performed their usual soccer-training. A detailed description of the usual soccer-training applied during the competition period is depicted in Table 2. To know the training load during the intervention, the session rating of perceived exertion (RPE) was determined (Table 1) by multiply the soccer training duration (minutes) by session RPE as described previously in young soccer players (18). We used the Chilean translation of the 10 point category ratio scale (CR10-scale) modified by Foster et al. (11).

Before the initiation of the training period, the TG subjects were instructed on proper execution of all the exercises included in the program. During intervention, the TG removed the technical drills (i.e. ball control; ball pass; ball conduction and dribbling; ball kicking; ball heading exercises) and replace them with plyometric drills within the usual 90-minute practice twice per week for seven weeks. This time frame and/or number of sessions are higher (3, 22, 42-

43) or very similar (6, 28) to those previously reported to induce significant explosive adaptations in young soccer players and youths (4). All plyometric sessions lasted 21 minutes and were performed just after the warm-up to ensure that the players were in a rested state and gain optimal benefits from the specific program, according to the training principle of priority (19). Plyometric drills included two sets of 10 repetitions of drop jumps from 20, 40 and 60 cm (i.e. 60 contacts) performed on a grass soccer field. Exercise intensity was determined as high (28) and exercise volume low (i.e. total ground contacts) (4). Although we did not increase the training volume during the 7-weeks period, as we used high intensity plyometric exercises performed with maximal effort, an adequate training stimulus was applied during each plyometric session, as previously demonstrated in young boys (4) and soccer players (22).

******Insert Table 2 near here******

The rest period between repetitions and sets was of 15 seconds (34) and 90 seconds (4), respectively, as previous research had demonstrated that this is an adequate rest interval for this type of training. The subjects were instructed to place their hands on their hips and step off the platforms with the supporting leg straight to avoid any initial upward propulsion or sinking, ensuring a drop height of 20, 40, and 60 cm. Participants were instructed to jump for maximal height and minimum contact time every jump to maximize reactive strength (i.e. bounce drop jumps). As players did not have any history of formal plyometrics, all exercises were supervised and particular attention was paid to demonstration and execution, giving maximal motivation to athletes during each jump. Training sessions were separated with a minimum of 48 hours (including games), to ensure the players were always fresh to train (28). Aside from the formal training intervention, all participants attended to their regular physical education classes.

Statistical Analyses

All values are reported as mean ± standard deviation (SD). Relative changes (%) in performance and standardized effects are expressed with 90% Confidence Limits (CL). Normality and homoscedasticity assumptions for all data before and after intervention were checked respectively with Shapiro-Wilk and Levene tests. To determine the effect of intervention (i.e. plyometric training) on explosive strength adaptations, a 2-way variance analysis with repeated measurements (2 groups × 2 times) was applied. When a significant F value was achieved across time or between groups, Tukey´s post hoc procedures were performed to locate the pairwise differences between the means. The α level was set at $p<0.05$ for statistical significance. All statistical calculations were performed using STATISTICA statistical package (Version 8.0; StatSoft, Inc, Tulsa). In addition to this null hypothesis testing, these data were also assessed for clinical significance using an approach based on the magnitudes of change. Threshold values for assessing magnitudes of standardized effects (SE - changes as a fraction or multiple of baseline standard deviation) were 0.20, 0.60, 1.2 and 2.0 for small, moderate, large and very large respectively (17). The effect was deemed unclear when the chance of benefit (a standardized improvement in performance of >0.20) was sufficiently high to warrant use of the intervention, but the risk of impairment was unacceptable. Such unclear effects were identified as those with an odds ratio of benefit to impairment of <66, a ratio that corresponds to an effect that is borderline possibly beneficial (25% chance of benefit) and borderline most unlikely detrimental (0.5% risk of harm). The effect was otherwise clear and reported as the magnitude of the observed value (17).

RESULTS

Before and after training no significant difference were observed between the intervention and control group in height, body mass, BMI or maturity status (Table 1). Also, no significant change within group was observed after the training period.

There was no significant difference between groups at baseline in all performance measures. Differences between groups became significant in RSI20 ($p<0.01$), RSI40 ($p<0.01$), MKD ($p<0.01$) and agility ($p<0.05$) after the 7-week period (Table 3).

******Insert Table 3 near here******

After training, the TG demonstrated a significant ($P<0.001$) and small increase in CMJ, RSI20, RSI40 and MB5, whereas no significant changes were observed in CG (Table 3). The training program did not induce a significant change in sprint performance for the TG, while the CG exhibits a significant ($P<0.001$) and small increase in 20m time (Table 3). The training program had a beneficial impact on the Illinois agility test time, resulting in a significant ($P<0.001$) and small decrease for the TG. In contrast, the CG achieve a significant ($P<0.001$) and small increase in the Illinois agility test time (Table 3).

After intervention, a significant ($P<0.001$) and small change was observed in MKD performance for the TG, whereas no significant change was observed in the CG (Table 3). After intervention, a significant ($P<0.001$) and small change was observed in 2.4 km performance time for the TG, whereas no significant change was observed in the CG (Table 3).

For the CMJ, RSI20, RSI40, MB5, 20-m sprint time, Illinois agility test time, MKD, 2.4 km time trial, 88%, 93%, 95%, 81%, 32%, 95%, 70% and 88%, respectively, of subjects from the TG were responders to training.

DISCUSSION

The current study indicated that 7-weeks of plyometric training induced significant and small to moderate improvements in CMJ, RSI20, RSI40, MB5, Illinois agility test time, MKD, and 2.4 km time trial performances. These results show that the combination of soccer drills and specific power training with no additional training time in-season optimize general and soccer-specific explosiveness and endurance performance in young soccer payers.

Although we used higher rigor to include subjects in the final analyses (i.e. completion of all training session) compared to previous interventions in young subjects (13, 47), the magnitude change in CMJ (SE = 0.20) and MB5 (SE = 0.28) in the current study was smaller than previously reported for both the CMJ (SE = 0.50-0.87) (3, 8, 28, 48) and MB5 (SE = 0.44-0.86) (8, 28) after explosive training with young soccer players using interventions of similar duration and/or number of sessions as in the present study. However, these discrepancy in training effect can be attributed to the training specificity, as the previous studies mentioned above used both slow and fast SSC (3, 8, 28, 48) which the former being similar to CMJ, as well as horizontal stimulus (8, 28). The greater magnitude in RSI20 and RSI40 (SE = 0.37-0.57) would support such contention considering the fast SCC of the current training program. In addition, Meylan and Malatesta (28), who did not include any drop jump training into their plyometric program, found no significant change in reactive strength. Considering the necessity to produce a high rate of power development in explosive actions (27), improvement in RSI may have enhance physical parameters of game performance. The improvement observed could have been induced by various neuromuscular adaptations, such as increased neural drive to the agonist muscles, improved intermuscular coordination, changes in the muscle-tendon mechanical-stiffness characteristics, changes in muscle size and/or architecture, and changes in single-fiber mechanics (24), but because no physiological measurements were made, only speculations are possibly.

The lack of improvement in 20-m sprint time after the current plyometric training demonstrated that other training stimulus may be necessary to enhance sprinting performance of young soccer players during the competitive period. A lack of change in 15-m sprint time after drop jump-based plyometric training has been previously reported in 17 years old soccer players (42). As the training stimulus was only vertical in nature, this may had reduced the chances for soccer players to gain adaptations considering the importance of horizontal force production and application in sprint performance (30) and the principle of training specificity (33, 36). Despite the lack of 20-m sprint improvement, a small reduction to complete the Illinois agility test was found in the TG. The current results are similar to those reported by Thomas et al. (42) where high intensity bounce drop jumps had a small positive effect on agility performance in young soccer players but only a trivial effect on 15-m sprint time. An increase in power development (31), reactive strength (49), and eccentric strength (39) may have contributed to the improvement in agility performance, while acceleration may be more dependent in a slower stretch-shorten cycle and rate of power production similar to the CMJ (5), which was not targeted in the current training program.

The improvement in kicking performance demonstrated that soccer-specific explosive actions of young male soccer players can be enhanced during the competitive period with a short-term plyometric training program implemented as a substitute for some soccer drills. An improvement in kicking performance after plyometric training has been previously reported in pre-adolescent (29) and adolescent soccer players (35). As players had more than a 2-year background of systematic soccer training and competition experience and given the lack of improvement in the CG, the positive change in kicking performance are unlikely to be related to the technical training over the short term period of 7-week in the current study. It had been suggested that an increased strength and power of legs' extensor muscles due to plyometric training may increase kicking performance in young soccer players, and these changes could be attributed solely to neuromuscular adaptations (29). It may be that these neuromuscular adaptations had an effect on biomechanical factors related to kicking performance, such as maximum linear velocity of the toe, ankle, knee and hip at ball contact (21), resultant in higher ball kicking velocity and hence MKD.

The TG exhibited a small reduction in 2.4 km time trial and became significantly fitter than the CG despite no additional aerobic training. The change in neuromuscular ability in the current study, especially the RSI, is likely to be transferred into a better running economy (37-38) which could potential explain the positive change in the 2.4 km time trial of the TG (32, 40). Previous explosive training in young soccer players did not induce improvement in VO_{2max} (29) or lactate thresholds (14) but was efficient at enhancing YoYo Intermittent Recovery Test Level 1 performance (48). This discrepency is likely related to the fact that change in neuromuscular power after an explosive training can contribute to the change of direction during an intermittent test (e.g. YoYo or 30-15 intermittent fitness test) with change of direction (2) or running economy (25, 40) but has a limited influence on VO_{2max} or lactate threshold (40, 44). Given the multi-directional nature of the game and necessity to cover long distances (41), explosive neuromuscular training should be considered as a complimentary method to aerobic conditioning in youth soccer players in addition to its anaerobic function.

PRACTICAL APPLICATIONS

The replacement of technical exercises with low volume high intensity plyometric drop jump exercises was effective at improving several explosive actions and endurance capacity in youth soccer players, which may have high transference into game-play performance. Thus, a twice weekly short-term high intensity PT program, implemented as a substitute for some soccer drills within regular in-season soccer practice, can enhance explosive and endurance performance in young soccer players compared with soccer training alone. The reduced volume of plyometric training ensured minimal time allocated to non-soccer specific training while maintaining continuous physical development of young players during the season. Considering that some young soccer teams (especially amateur teams) had limited time to train (e.g. 90 min, two times per week), the current findings may be relevant to programming PT in this context.

Although concern has been expressed by some researchers with regard to the injury risk during plyometric training, to the best of the author's knowledge, when adequate controlled plyometric training intervention had been applied, no important injuries had been reported. More so, plyometric training had been advocated as a preventive injury strategy, and even as a rehabilitation tool. In fact, during our intervention, the relative high intensity of the training program did not result in any injuries, and it is important to notice that in the present investigation subjects reported little subjective muscle pain after the training sessions (data not shown). However, practitioners need to be mindful of the players' movement competency before introducing drop jump exercises and place a considerable emphasis on coaching.

Also, in accordance to the concept of training specificity, drop jump training was most effective at improving tests replicating the training stimulus (RSI) and transferred to performance measures where vertical neuromuscular power and reactive strength were relevant (CMJ, 5MB, MKD, 2.5 km time trial). However, another or a complimentary training stimulus should be implemented to improve 20-m sprint time in young soccer players. Future studies should include training programs with multi-directional and unilateral-bilateral exercises given the nature of sprinting and other explosive movement on the field (e.g. tackling, change of direction). Finally, short-term plyometric training program can also be considered as an intervention strategy to increase kicking ability and endurance in youth soccer players, but we recommend that this training method must be adequately incorporated in a comprehensive training program that develop the specific technical abilities critical to achieve adequate kicking performance (especially at young ages) and with an adequate aerobic conditioning program, to optimize training adaptations.

ACKNOWLEDGMENTS

The authors declare that they do not have any conflict of interest in accordance with the journal policy, and disclose no professional relationships with companies or manufacturers who will benefit from the results of the present study. The results of the present study do not constitute endorsement of the product by the authors or the National Strength and Conditioning Association.

REFERENCES

1. Brughelli M, Cronin J, Levin G, and Chaouachi A. Understanding change of direction ability in sport: a review of resistance training studies. *Sports Med* 38: 1045-1063, 2008.
2. Buchheit M. The 30-15 intermittent fitness test: accuracy for individualizing interval training of young intermittent sport players. *J Strength Cond Res* 22: 365-374, 2008.
3. Buchheit M, Mendez-Villanueva A, Delhomel G, Brughelli M, and Ahmaidi S. Improving repeated sprint ability in young elite soccer players: repeated shuttle sprints vs. explosive strength training. *J Strength Cond Res* 24: 2715-2722, 2010.
4. Campillo RR, Andrade DC, and Izquierdo M. Effects of plyometric training volume and training surface on explosive strength. *J Strength Cond Res*, 2012.
5. Cronin JB and Hansen KT. Strength and power predictors of sports speed. *J Strength Cond Res* 19: 349-357, 2005.

6. Chelly MS, Fathloun M, Cherif N, Ben Amar M, Tabka Z, and Van Praagh E. Effects of a back squat training program on leg power, jump, and sprint performances in junior soccer players. *J Strength Cond Res* 23: 2241-2249, 2009.

7. de Villarreal ES, Gonzalez-Badillo JJ, and Izquierdo M. Low and moderate plyometric training frequency produces greater jumping and sprinting gains compared with high frequency. *J Strength Cond Res* 22: 715-725, 2008.

8. Diallo O, Dore E, Duche P, and Van Praagh E. Effects of plyometric training followed by a reduced training programme on physical performance in prepubescent soccer players. *J Sports Med Phys Fitness* 41: 342-348, 2001.

9. Faude O, Koch T, and Meyer T. Straight sprinting is the most frequent action in goal situations in professional football. *J Sports Sci* 30: 625-631, 2012.

10. FIFA. *Laws of the game 2012/2013*. Zurich, Switzerland: Federation Internationale de Football Association. International Football Association Board, 2012.

11. Foster C, Florhaug JA, Franklin J, Gottschall L, Hrovatin LA, Parker S, Doleshal P, and Dodge C. A new approach to monitoring exercise training. *J Strength Cond Res* 15: 109-115, 2001.

12. Gehri DJ, Ricard MD, Kleiner DM, and Kirkendall DT. A comparison of plyometric training techniques for improving vertical jump ability and energy production. *The Journal of Strength & Conditioning Research* 12: 85-89, 1998.

13. Gonzalez-Badillo JJ, Gorostiaga EM, Arellano R, and Izquierdo M. Moderate resistance training volume produces more favorable strength gains than high or low volumes during a short-term training cycle. *J Strength Cond Res* 19: 689-697, 2005.

14. Gorostiaga EM, Izquierdo M, Ruesta M, Iribarren J, Gonzalez-Badillo JJ, and Ibanez J. Strength training effects on physical performance and serum hormones in young soccer players. *Eur J Appl Physiol* 91: 698-707, 2004.

15. Hachana Y, Chaabene H, Nabli MA, Attia A, Moualhi J, Farhat N, and Elloumi M. Test-retest reliability, criterion related validity and minimal detectable change of the Illinois agility test in male team sport athletes. *J Strength Cond Res*, 2013.

16. Hansen L, Bangsbo J, Twisk J, and Klausen K. Development of muscle strength in relation to training level and testosterone in young male soccer players. *J Appl Physiol* 87: 1141-1147, 1999.

17. Hopkins WG, Marshall SW, Batterham AM, and Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 41: 3-13, 2009.

18. Impellizzeri FM, Rampinini E, Coutts AJ, Sassi A, and Marcora SM. Use of RPE-based training load in soccer. *Med Sci Sports Exerc* 36: 1042-1047, 2004.

19. Kraemer WJ and Ratamess NA. Fundamentals of resistance training: progression and exercise prescription. *Med Sci Sports Exerc* 36: 674-688, 2004.

20. le Gall F, Carling C, Williams M, and Reilly T. Anthropometric and fitness characteristics of international, professional and amateur male graduate soccer players from an elite youth academy. *J Sci Med Sport* 13: 90-95, 2010.

21. Lees A, Asai T, Andersen TB, Nunome H, and Sterzing T. The biomechanics of kicking in soccer: a review. *J Sports Sci* 28: 805-817, 2010.

22. Maio Alves JM, Rebelo AN, Abrantes C, and Sampaio J. Short-term effects of complex and contrast training in soccer players' vertical jump, sprint, and agility abilities. *J Strength Cond Res* 24: 936-941, 2010.

23. Markovic G, Dizdar D, and Jaric S. Evaluation of tests of maximum kicking performance. *J Sports Med Phys Fitness* 46: 215-220, 2006.

24. Markovic G and Mikulic P. Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Med* 40: 859-895, 2010.

25. Marta C, Marinho DA, Barbosa TM, Izquierdo M, and Marques MC. Effects of concurrent training on explosive strength and VO2max in prepubescent children. *Int J Sports Med*, 2013.

26. Mero A, Komi PV, and Gregor RJ. Biomechanics of sprint running. A review. *Sports Med* 13: 376-392, 1992.

27. Meylan C, Cronin J, Manson S, Oliver J, and Hughes M. An integrative model of power development in youth football. *Int J Sports Sci Coach*, In Press.

28. Meylan C and Malatesta D. Effects of in-season plyometric training within soccer practice on explosive actions of young players. *J Strength Cond Res* 23: 2605-2613, 2009.

29. Michailidis Y, Fatouros IG, Primpa E, Michailidis C, Avloniti A, Chatzinikolaou A, Barbero-Alvarez JC, Tsoukas D, Douroudos, II, Draganidis D, Leontsini D, Margonis K, Berberidou F, and Kambas A. Plyometrics' trainability in preadolescent soccer athletes. *J Strength Cond Res* 27: 38-49, 2013.

30. Morin JB, Bourdin M, Edouard P, Peyrot N, Samozino P, and Lacour JR. Mechanical determinants of 100-m sprint running performance. *Eur J Appl Physiol* 112: 3921-3930, 2012.

31. Negrete R and Brophy J. The relationship between isokinetic open and closed chain lower extremity strength and functional performance. *J Sport Rehabil* 9: 46-61, 2000.

32. Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, and Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol* 86: 1527-1533, 1999.

33. Randell AD, Cronin JB, Keogh JW, and Gill ND. Transference of Strength and Power Adaptation to Sports Performance-Horizontal and Vertical Force Production. *Strength Cond J* 32: 100-106, 2010.

34. Read MM and Cisar C. The influence of varied rest interval lengths on depth jump performance. *Journal of Strength and Conditioning Research* 15: 279-283, 2001.

35. Rubley MD, Haase AC, Holcomb WR, Girouard TJ, and Tandy RD. The effect of plyometric training on power and kicking distance in female adolescent soccer players. *J Strength Cond Res* 25: 129-134, 2011.

36. Saez de Villarreal E, Requena B, and Cronin JB. The effects of plyometric training on sprint performance: a meta-analysis. *J Strength Cond Res* 26: 575-584, 2012.

37. Saunders PU, Pyne DB, Telford RD, and Hawley JA. Factors affecting running economy in trained distance runners. *Sports Med* 34: 465-485, 2004.

38. Saunders PU, Telford RD, Pyne DB, Peltola EM, Cunningham RB, Gore CJ, and Hawley JA. Short-term plyometric training improves running economy in highly trained middle and long distance runners. *J Strength Cond Res* 20: 947-954, 2006.

39. Sheppard JM and Young WB. Agility literature review: Classifications, training and testing. *J Sport Sci* 24: 919-932, 2006.

40. Spurrs RW, Murphy AJ, and Watsford ML. The effect of plyometric training on distance running performance. *Eur J Appl Physiol* 89: 1-7, 2003.

41. Stolen T, Chamari K, Castagna C, and Wisloff U. Physiology of soccer: an update. *Sports Med* 35: 501-536, 2005.

42. Thomas K, French D, and Hayes PR. The effect of two plyometric training techniques on muscular power and agility in youth soccer players. *Journal of Strength and Conditioning Research* 23: 332-335, 2009.

43. Tonnessen E, Shalfawi SA, Haugen T, and Enoksen E. The effect of 40-m repeated sprint training on maximum sprinting speed, repeated sprint speed endurance, vertical jump, and aerobic capacity in young elite male soccer players. *J Strength Cond Res* 25: 2364-2370, 2011.

44. Turner AM, Owings M, and Schwane JA. Improvement in running economy after 6 weeks of plyometric training. *J Strength Cond Res* 17: 60-67, 2003.

45. Vaeyens R, Malina RM, Janssens M, Van Renterghem B, Bourgois J, Vrijens J, and Philippaerts RM. A multidisciplinary selection model for youth soccer: the Ghent Youth Soccer Project. *Br J Sports Med* 40: 928-934; discussion 934, 2006.

46. Weeks BK and Beck BR. The relationship between physical activity and bone during adolescence differs according to sex and biological maturity. *J Osteoporos* 2010: 546593, 2010.

47. Weeks BK, Young CM, and Beck BR. Eight months of regular in-school jumping improves indices of bone strength in adolescent boys and Girls: the POWER PE study. *J Bone Miner Res* 23: 1002-1011, 2008.

48. Wong PL, Chamari K, and Wisloff U. Effects of 12-week on-field combined strength and power training on physical performance among U-14 young soccer players. *J Strength Cond Res* 24: 644-652, 2010.

49. Young WB, James R, and Montgomery I. Is muscle power related to running speed with changes of direction? *J Sports Med Phys Fitness* 42: 282-288, 2002.

TABLES

Table 1. Subject characteristics at the start of the 7-week period (mean ± SD).

	Control group (n=38)	Training group (n=38)
Age (y)	13.2 ± 1.8	13.2 ± 1.8
Genital Tanner stage	3.7 ± 1.0	3.7 ± 1.1
Pubic Hair Tanner stage	3.6 ± 1.1	3.6 ± 1.1
Body Mass (kg)	47.4 ± 11.9	47.9 ± 10.0
Height (cm)	153 ± 12	154 ± 12
BMI (m.kg^{-2})	19.9 ± 2.3	19.9 ± 1.7
Session rating of perceived exertion	312 ± 123	334 ± 151
Soccer experience (y)	4.1 ± 1.8	4.4 ± 1.6

No significant difference between groups and within groups before and after the 7-week period.

Table 2. Usual soccer training session of young soccer players during intervention.

Exercise	**Duration (min)**
Technical drills (ball control; ball pass; ball conduction and dribbling; ball kicking; ball heading)	20
Tactical drills (defensive drills; offensive drills; corner kicks situations; penalty kicks)	20
Small-sided games with or without goal keeper, and with or without change of soccer rules (e.g. one touch pass; only heading goals)	20
Simulated competitive games	30

Table 3. Baseline performance measures (mean ± SD) and training effect (90% confidence limits) after the 7-week period

Variables	Control Group (n = 38)		Training Group (n = 38)	
	Baseline	Training effect (%) Effect size	Baseline	Training effect (%) Effect size
Countermovement jump (cm)	26.6 ± 4.7	2.2 (0.4, 3.9) 0.12 (0.02, 0.22)	27.0 ± 5.8	4.3[a] (3.2, 5.3) 0.20 (0.15, 0.25)
RSI20 ($mm.ms^{-1}$)	1.01 ± 0.38	-2.7 (-6.5, 1.3) -0.07 (-0.17, 0.03)	1.04 ± 0.40	22.2[a] (17.6, 26,9)[c] 0.57 (0.46, 0.68)
RSI40 ($mm.ms^{-1}$)	1.02 ± 0.35	-2.4 (-6.7, 2.2) -0.07 (-0.2, 0.06)	1.04 ± 0.40	16.0[a](12.5, 19.5)[c] 0.37 (0.29, 0.44)
5 multiple bounds (m)	8.71 ± 1.20	0.1 (-0.4, 0.6) 0.01 (-0.03, 0.04)	9.00 ± 1.24	4.1[a] (2.9, 5.4) 0.28 (0.19, 0.36)
20-m sprint time (s)	4.39 ± 0.48	3.7[a](2.2, 5.2) 0.35 (0.21, 0.48)	4.32 ± 0.57	-0.4 (-1.1, 0.3) -0.03 (-0.08, 0.02)
Illinois agility test time (s)	20.1 ± 2.7	3.5[a](2.9, 4.2) 0.25 (0.20, 0.30)	20.3 ± 2.8	-3.5[a](-4.2, -2.8)[b] -0.26 (-0.31, -0.21)
Maximal kicking distance test (m)	30.9 ± 7.4	-1.6 (-3.0, -0.1) -0.06 (-012, 0.00)	32.7 ± 7.7	13.5[a](10.6, 16.4)[c] 0.53 (0.42, 0.63)
2.4 km time trial (min)	10.7 ± 0.8	-0.3 (-0.8, 0.2) -0.04 (-0.10, 0.03)	10.6 ± 0.8	-1.9[a](-2.6, -1.2) -0.27 (-0.37, -0.18)

RSI20: 20 cm drop jump reactive strength index; RSI40: 40 cm drop jump reactive strength index
[a]: denotes significant difference vs. baseline value ($p<0.01$)
[b]: denotes significant difference vs. Control Group ($p<0.05$)
[c]: denotes significant difference vs. Control Group ($p<0.01$)

Study IV. Ramírez-Campillo R, Meylan C, Álvarez-Lepín C, Henriquez-Olguín C, Martinez C, Andrade DC, Castro-Sepúlveda N, Burgos C, Baez EI, Izquierdo M (2013). The effects of interday rest on adaptation to 6-weeks of plyometric training in young soccer players. J Strength Cond Res. Epub ahead of print. (Impact Factor: 1.831, Journal ranking: 2nd Quartile; Sports Sciences).

Study V. Ramírez-Campillo R, Andrade DC, Álvarez C, Henriquez-Olguín C, Martínez C, Báez EI, Silva-Urra J, Burgos C, Izquierdo M (2013). The effects of interset rest on adaptation to 7-weeks of explosive training in young soccer players. Submitted.

SUBMITTED TO THE:

JOURNAL OF SPORTS SCIENCE & MEDICINE

Free Electronic Journal (ISSN 1303-2968)

Indexed in SCI Expanded, Focus on: Sports Science & Medicine, SciSearch, PubMed Central, ProQuest (Physical Education Index), CAB Abstracts SCOPUS, Index Copernicus, SPORTDiscus, DOAJ, J-Gate, GoogleScholar, EBSCO, GALE, ERA and SPONET.

2012 IF (2-Year): 0.953 **IF (5-Year):** 1.362 **2011 SJR:** 0.047 **Average Citations per item:** 3.40

THE EFFECTS OF INTERSET REST ON ADAPTATION TO 7-WEEKS OF EXPLOSIVE TRAINING IN YOUNG SOCCER PLAYERS

Ramírez-Campillo R[a], Andrade DC[b], Álvarez C[c], Henriquez-Olguín C[d], Martínez C[e], Báez-SanMartín E[f], Silva-Urra J[g], Burgos C[d], Izquierdo M[h]

RUNNING HEAD: EXPLOSIVE TRAINING IN YOUNG SOCCER PLAYERS

[a] Department of Physical Activity Sciences, Universidad de Los Lagos, Osorno, Chile.

[b] Cellular Physiology Laboratory, Biomedical Department, Faculty of Health Science, Universidad de Antofagasta, Antofagasta, Chile.

[c] Family Health Center of Los Lagos, Health Promotion Program, Los Lagos, Chile

[d] Laboratory of Exercise Sciences, MEDS Clinic, Las Condes, Chile.

[e] Physical Education Department, University of La Frontera, Temuco, Chile.

[f] Department of Sport and Recreation, University of Playa Ancha, Valparaíso, Chile.

[g] Biomedical Department, Faculty of Health Science, Universidad de Antofagasta, Antofagasta, Chile.

[h] Public University of Navarre, Department of Health Sciences, Spain.

Corresponding author

Mikel Izquierdo, PhD

Department of Health Sciences

Public University of Navarra (Navarra) SPAIN

Campus of Tudela

Av. de Tarazona s/n. 31500 Tudela (Navarra) SPAIN

Tel + 34 948 417876

mikel.izquierdo@gmail.com

Abstract

The aim of the study was to determine the effects of plyometric training using 30, 60, or 120 s of rest between sets on explosive adaptations in young soccer players. Four groups of athletes were randomly formed: control (CG; n = 15), plyometric training with 30 s (G30; n = 13), 60 s (G60; n = 14), and 120 s (G120; n = 12) of rest between training sets. Before and after intervention players were measured in jump ability, 20-m sprint time, change of direction speed (CODS), and kicking performance. The training program was applied during 7 weeks, 2 sessions per week. After intervention the G30, G60 and G120 groups showed a significant improvement in jump, CODS, and kicking performance, with no differences between treatments. The study shows that 30, 60, and 120 s of rest between sets ensure significant and similar adaptations during high-intensity short-term explosive training in young male soccer players.

Key words: biological age, explosive strength, team sports, childhood, strength training.

INTRODUCTION

The capacity to produce varied powerful actions during a 90-minute game is associated with high aerobic capacity (Stolen et al., 2005). However, the ability to produce explosive single-bout effort is as important as aerobic power for success in soccer (Faude et al., 2012), such as sprinting, jumping, or changing direction (Stolen et al., 2005). In addition, future international and professional players had superior explosive characteristics (i.e. speed, power) at youth level than future amateur players (le Gall et al., 2010). Plyometric training (PT) is commonly used to increase these types of actions in young soccer players (Diallo et al., 2001; Meylan and Malatesta, 2009; Michailidis et al., 2013; Thomas et al., 2009), with the advantage of being easy to integrate in soccer practice (space, time, equipment), and replicating the neuromuscular stimulus encountered in explosive soccer activities such as jumping and sprinting (Gehri et al., 1998). Therefore, PT may be advocated as an appropriate approach for enhancing soccer-related performance abilities. However, although the primary governing factors regulating the performance of repeated power-oriented drills are their intensiy, duration and recovery duration (ACSM, 2009), the characteristics of between sets recovery of a PT that generates optimal gains are not clear (Saez de Villarreal et al., 2012), especially in young soccer players.

To the best of the authors' knowledge a limited number of studies have established the optimum PT design (i.e. interset rest intervals) for explosive strength enhancement (de Salles et al., 2009). Rest interval can have a significant acute effect on metabolic, hormonal, cardiovascular, and performance responses to strength exercise (Kraemer et al., 1987; Garcia-Lopez et al., 2007; Kraemer and Ratamess, 2005). Therefore, adequate rest may be vital to ensure the quality of each repetition being performed in exercise sets designed to develop muscle power (ACSM, 2009). Two to five min of rest had been recommended between sets when training for muscle power (ACSM, 2009). However, only a few longitudinal studies suggest that different resting intervals between sets will significantly affect gains in muscle performance (de Salles et al., 2009). Thus, although statements regarding rest interval between power-PT sets have been made, the scientific evidence to sustain these recommendations is limited, especially in young soccer players were the research is scarce.

In adult soccer players a recovery period of 25-30 s was adequate to maintain plyometric performance during repeated 15-m sprints (Abt et al., 2011), and a 10 s recovery period was adequate to induce significant increases in sprint performance after 8 weeks of sprint training (Saraslanidis et al., 2011). In youths, the recovery capacity from high intensity plyometric exercises has been reported to be higher than in adults (Marginson et al., 2005). A higher level of flexibility, slower muscle fiber-type composition, and a high level of habitual physical activity in youths may help explain their higher recovery ability after high intensity PT (Marginson et al., 2005). Therefore, as young athletes recover from physical exertion can be faster than adults, especially from high-intensity exercise (Falk and Dotan, 2006), one may hypothesize that brief (i.e. 30 s) interset rest intervals between PT drills could be viewed as an adequate recovery period to induce training adaptations in this population, specially when the duration of jump drills are taken into account (i.e. <1 s) (Chaouachi et al., 2011; Balsom et al., 1992). Thus, this study was designed to address the question of how different interset rest intervals of a PT program affects explosive strength, running speed, change of direction speed (CODS), and sport specific performance skills in young soccer players.

Methods

Subjects and experimental design

Initially 90 male participants between 8 and 14 years of age fulfilled the inclusion criteria to participate in the study. Participants with more than 2 years of soccer experience were recruited from an amateur soccer team, submitted to the same soccer drills (i.e. 2 training sessions per week, in addition to one or two competitive games per week), resulting in similar soccer-specific weekly training load (session rating of perceived exertion) for all groups in the study design. Athletes also participate in their regular weekly physical education classes. To be included in the final analyses participants were required to complete >90% of all the training sessions and attend to all measurements sessions. As a result of these requirements 36 participants were removed from the study. Therefore 54 young male soccer players were included for the final analyses. Participants were randomly assigned to four groups: control group (CG; n = 15), 30s rest interval group (G30; n = 13), 60s rest interval group (G60; n = 14) and 120s rest interval group (G120; n = 12). Subject characteristics are provided in Table 1. None of the participants had any background in regular weight training or competitive sports that involved any of the training methods used in the investigation.

******Table 1 about here******

Exclusion criteria included participants with 1) potential medical problems or a history of ankle, knee, or back pathology in the 3 months prior to the study, and 2) medical or orthopedic problems that compromised their participation or performance in the study. All participants (and their parents or guardians) were fully informed about the experimental procedures and possible risks and benefits associated with the study. They were then invited to sign an informed consent document before any of the tests were performed. The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Department of Physical Activity Sciences from University of Los Lagos, Osorno, Chile.

Testing procedures

All tests were carried out between 18:00-20:00 h. All participants (and their parents or guardians) were instructed to a) have a good night's sleep (≥9 h) before each testing day, b) avoid drinking or eating at least 2-3 h before measurements, c) use the same sport shoes during the pre and post intervention testing. All participants were motivated to give their maximum effort during performance measurements.

For performance measurements, participants were carefully familiarized with the test procedures during two practice sessions per week during two weeks, performing 20 min of technique training for the testing exercises to be used during measurement. The participants also completed several explosive type actions during these four sessions to become familiar with the exercises used during training. Participants did not report subjective feelings of muscle damage after the familiarization sessions. Considering that the ability to produce explosive single-bout effort such as sprinting, jumping, kicking, or changing direction is as important as aerobic power for success in soccer (Faude et al., 2012; Stolen et al., 2005), the following performance tests were applied: countermovement jump (CMJ) for maximal vertical distance (cm); 20 (RSI20) and 40 (RSI40) cm drop jump reactive strength index (mm/ms); maximal kicking distance (m); 20-m sprint time (s); L-run CODS (s). Ten minutes of standard warm-up were executed before each testing day.

Anthropometrics

Height was measured using a wall-mounted stadiometer (Butterfly, Shanghai, China) recorded to the nearest 0.5 cm, body mass was measured to the nearest 0.1 kg using a digital scale (BC-554 Ironman Body Composition Monitor, Tanita, Illinois, USA) and body mass index (BMI) was calculated (kg/m^2). Maturity was determined by self-assessment of Tanner stage (Weeks and Beck, 2010).

Jumps

Testing included the execution of maximal CMJ, RSI20, and RSI40. All jumps were performed on a mobile contact mat (Globus, Codogne, Italy) with arms akimbo. Take-off and landing was standardized to full knee and ankle extension on the same spot. The participants were instructed to maximize jump height and minimize ground contact time during the RSI20 and RSI40 after dropping down from a 20 and 40 cm drop box. The RSI20 and RSI40 were calculated as previously reported (Young et al., 2002).

Sprint

The sprint time was measured to the nearest 0.01 s using single beam infrared reds photoelectric cells (Globus Italia, Codogne, Italy). The starting position was standardized to a still split standing position with the toe of the preferred foot forward and behind the starting line. Sprint start was given by a random sound which triggers timing. The photoelectectric signal was positioned at 20 m and set approximately 0.7 m above the floor (i.e. hip level) to capture the trunk movement rather than a false trigger from a limb.

Change of direction speed (CODS)

CODS times were recorded from the L-run test, following previously described instructions (Gabbett et al., 2008). The timing system and procedures where the same as the 20-m sprint.

Kicking distance

After a standard warm-up, each player kicked a new size five soccer ball (Nike Seitiro, FIFA certified) (FIFA, 2012) for maximal distance on a soccer field, according to previous indications (Ball, 2009). Basically, two markers were placed on the ground side by side to define the kick line. Participants performed a maximal instep kick with their dominant leg after a run up of two strides. A 75 m metric tape was placed between the kicking line and across the soccer field. An assessor was placed near the region where the ball land after the kick to mark the point of contact and to measure the distance kicked. The distance was measured to the nearest 0.2 m. All measurements were completed with a wind velocity <20 km/h (Chilean Meteorological Service, Santiago, Chile).

Plyometric training program

The intervention took place during the competitie period. During the intervention participants kept their usual soccer training (i.e. two weekly training sessions of 90 min, consisting in 30 min of technical-tactical exercises, 30 min of small-sided games, and 30 min of simulated competitive games) and competition schedule. The PT was completed two days per week for the PT groups, with 48 hours of rest between sessions as previously recommended (Wathen, 1993; Faigenbaum, 2006), and just after the warm-up to ensure that the players were in a rested state and gain optimal benefits from the specific program, according to the priority training principle. The same warm up was completed by the CG and plyometrically trained groups. While the CG keep their regular soccer drills, the G30, G60, and G120 groups replaced the technical-tactical drills by plyometric exercises. After the plyometric drills, participants from the G30, G60, G120, and CG completed the same soccer training sessions.

Participants were instructed to jump for maximal height and minimum contact time every jump to maximize reactive strength (i.e. bounce drop jumps). Athletes complete a total of 60 jumps per session (2 sets of 10 jumps from 20, 40, and 60 cm boxes). As players did not have any history of formal plyometrics, all exercises were supervised and particular attention was paid to demonstration and execution, giving maximal motivation to athletes during each jump. Although we did not increase the training volume during the 7-weeks period, as we used high intensity plyometric exercises performed with maximal effort, an effective and safe training stimulus was applied during each plyometric session, as previously demonstrated in similar plyometric training interventions in young boys (Campillo et al., 2012) and soccer players (Thomas et al., 2009). The exercise were completed 2 times per week, for a total of 7 weeks. This time frame and/or number of sessions are higher (Tonnessen et al., 2011; Maio Alves et al., 2010; Thomas et al., 2009) or very similar (Buchheit et al., 2010; Meylan and Malatesta, 2009; Chelly et al., 2009) to those previously reported to induce significant explosive adaptations in young soccer players and youths (Campillo et al., 2012).

The different rest periods between sets of plyometric drills for the three experimental groups were choose based on previous recommendations (ACSM, 2009; Abt et al., 2011; Read and Cisar, 2001), corresponding to 30 s, 60 s, and 120 s of rest between sets for the G30, G60 and G120 groups, respectively. The rest between repetitions was of 15 s (Read and Cisar, 2001). A low intensity active interset and interrepetition rest was used to favor recovery (Bogdanis et al., 1996).

To assure the safetty of plymetric sessions, subjects were asked to classify their actual pain level though a visual analog scale (VAS). A continuous line of 10 cm were presented to athletes with the Spanish words for “no pain” in the cm 0 and with the Spanish word for “maximal pain” in the cm 10. Subjects were asked to classify their pain while they were sitting. Similar protocols had been applied previously (Grant et al., 1999; Itoh et al., 2008; Marginson et al., 2005). We measure the intensity of muscle pain from the lower extremities before the first session of plyometric training, immediately after, 24h, 48h, 72h, and 96h after the first session. Also, during the last week of training we repeated the protocol. Subjects report relatively a low pain level (between 0-2). This seems common in youths (Eston et al., 2003; Marginson and Eston, 2001; Marginson et al., 2005).

Statistical analysis

All values were reported as mean ± SD. Relative changes (%) in performance and standardized effects (SE) are expressed with a 90% Confidence Limits (CL). Normality and homoscedasticity assumptions for all data before and after intervention were checked respectively with Kolmogorov-Smirnov and Levene tests. To determine the effect of intervention on performance adaptations, a 2-way variance analysis with repeated measurements (4 groups × 2 times) was applied. When a significant F value was achieved across time or between groups, Tukey post hoc procedures were performed to locate the pairwise differences between the means. The α level was set at $p<0.05$ for statistical significance. In addition to this null hypothesis testing, data was also assessed for clinical significance using an approach based on the magnitudes of change. Threshold values for assessing magnitudes of SE (changes as a fraction or multiple of baseline standard deviation) were 0.20, 0.60, 1.2 and 2.0 for small, moderate, large and very large respectively (Hopkins et al., 2009).

Results

Despite not pair-matching individuals based on an independent variable, there were no significant differences ($P > 0.05$) between groups' descriptive data (Table 1).

Before training no significant differences ($P > 0.05$) were observed between groups in CMJ, RSI20, RSI40, 20-m sprint time, CODS time, or kicking test (Table 2).

******Table 2 near here******

No significant change in the CG was observed, except for an increase ($P = 0.029$) in 20-m sprint test time (i.e. reduced performance), with a moderate clinically significant change (+0.65 SE).

The 2-way variance analysis with repeated measurements (4 groups × 2 times) showed a similar statistically significant increase for G30, G60 and G120 in CMJ ($P = 0.041$; 0.022; 0.032, respectively), RSI20 ($P < 0.001$), RSI40 ($P < 0.001$), CODS ($P = 0.025$; 0.029; 0.019, respectively), and kicking performance ($P = 0.034$; 0.021; 0.033, respectively) after training. None of the plyometrically trained groups achieve a statistically significant change in 20-m sprint performance. Also, the magnitudes of change analyses showed that G30, G60 and G120 groups achieve a similar small to moderate clinically significant change in CMJ (+0.49; +0.58; +0.55 SE, respectively), RSI20 (+0.81; +0.86; +0.89 SE, respectively), RSI40 (+0.86; +0.88; +0.98 SE, respectively), CODS (-1.03; -0.87; -1.04 SE, respectively), and maximal kicking distance (+0.39; +0.49; +0.43 SE, respectively) performance after training.

Discussion

The current study suggests that 7 weeks of PT, with either 30, 60 or 120 s of rest between sets of low-volume and high-intensity plyometric drills, induced significant and small to moderate similar improvements in CMJ, RSI20, RSI40, CODS time, and kicking test performances in young male soccer players. Also, these results show that the combination of soccer drills and specific explosive strength training with no additional training time in-season is a meaningful stimulus to enhance explosive strength adaptations in young male soccer payers.

Although 2 to 5 min of rest has been recommended to ensure the quality of each repetition being performed in exercise sets designed to develop muscle power (ACSM, 2009), and although several power-oriented studies indicate superior acute effects with long vs. short rest between training sets (Abdessemed et al., 1999; de Salles et al., 2009; Pincivero et al., 1999; Pincivero et al., 1998), our results show that 30, 60, and 120 s of rest between sets of high intensity plyometric jumps ensure significant and similar adaptations during 7 weeks of training in young male soccer players. It may be argued that the PT applied represented a low training load; therefore a relatively short period of recovery between training sets to achieve performance adaptations was sufficient. However, during training players completed 60 jumps each session, including bounce drop jumps from 20, 40, and 60 cm, which can be considered high intensity exercises (aside from the maximal voluntary intensity required to complete all jumps). This load is similar to that reported in previously effective training intervention with young soccer players (Thomas et al., 2009) and adolescents (Campillo et al., 2012). Therefore, several possible mechanisms can be postulated to understand how a relatively short rest period between PT sets allow significant explosive performance adaptations in young male soccer players, like a reduced susceptibility to muscle damage, performance alterations, and higher ability to recover after plyometric drills (Marginson et al., 2005); reduced proportion of fast twitch fibers (Lexell et al., 1992); reduced relative power generation capacity related to maturation-dependent neuromotor factors (Falk and Dotan, 2006); reduced body mass (Webber et al., 1989); greater muscle compliance (allowing rapid bone growth) (Eston et al., 2003); reduced metabolic stress asociated with the short duration high velocity stretch-shortening cycle (SSC) muscle actions performed during training sets (Chaouachi et al., 2011; Balsom et al., 1992); the utilizacion during training of low intensity active interset and interrepetition rest to favor recovery (Bogdanis et al., 1996); and adaptations achieved during training such as endurance capacity (Wong et al., 2010) and, hence, an improved ability to recover from high intensity exercise (Tomlin and Wenger, 2001). Interestingly, it has been suggested that muscle function (i.e. jump ability, sprint performance) is probably the best indicator of muscle recovery after intense exercise, especially in athletes (Eston et al., 2003); hence, future studies in young soccer players may consider the evaluation of muscle function performance after plyometric drills with different rest times between sets to better understand the recuperation process in this population segment.

The G30, G60, and G120 groups significantly increased jumping performance (CMJ, RSI20, and RSI40), with no difference between groups. The magnitude of change in performance was similar to that previously reported in young soccer players submitted to power-oriented interventions (Buchheit et al., 2010; Meylan and Malatesta, 2009; Rubley et al., 2011), of similar duration and/or number of sessions as in the present study (Buchheit et al., 2010; Meylan and Malatesta, 2009; Rubley et al., 2011). The improvement observed, which may improve player performance, could have been induced by various neuromuscular adaptations, such as increased neural drive to the agonist muscles, improved intermuscular coordination, and/or changes in the muscle-tendon mechanical-stiffness characteristics (Markovic and Mikulic, 2010); but because no physiological measurements were made, only speculations are possible.

The lack of improvement in 20-m sprint time after PT demonstrated that other training stimulus may be necessary to enhance sprinting performance. A lack of change in sprint time after drop jump-based PT has been previously reported in 17 years old soccer players (Thomas et al., 2009). As the training stimulus was only vertical in nature, this may had reduced the chances to gain adaptations considering the importance of horizontal force production and application in sprint performance (Morin et al., 2012) and the principle of training specificity (Randell et al., 2010; Saez de Villarreal et al., 2012). Despite the lack of 20-m sprint improvement, all plyometrically trained groups exhibit a significant and similar reduction to complete the CODS test. The current results are similar to those previously reported (Thomas et al., 2009), where high intensity bounce drop jumps had a small positive effect on agility performance in young soccer players but only a trivial effect on 15-m sprint time. An increase in power development (Negrete and Brophy, 2000) reactive strength (Young et al., 2002) and eccentric strength (Sheppard and Young, 2006), may have contributed to the improvement in CODS performance, while acceleration may be more dependent in a slower stretch-shorten cycle and rate of power production similar to the CMJ (Cronin and Hansen, 2005), which was not targeted in the current training program. Contrary to the positive explosive adaptations observed in the plyometrically trained groups, the CG exhibited a significant increase in their 20-m sprint test time. These observations reinforce the value of an independent power training program to enhance explosive actions of young soccer players during their in season training.

As a novelty, our results show that kicking performance can be similarly enhanced during the competitive period with a PT program implemented as a substitute for some soccer drills, either using 30, 60 or 120 s of rest between sets. An improvement in kicking performance after PT has been previously reported in pre-adolescent (Michailidis et al., 2013) and adolescent soccer players (Rubley et al., 2011). As players had more than a 2-year background of systematic soccer training and competition experience, and given the lack of improvement in the CG, the increased performance is unlikely to be related to the technical training over the short term period of 7-week. It had been suggested that an increased strength and power of legs' extensor muscles due to PT may increase kicking performance, and these changes could be attributed solely to neuromuscular adaptations (Michailidis et al., 2013); and these adaptations may had an effect on biomechanical factors related to kicking performance, such as maximum linear velocity of the toe, ankle, knee and hip at ball contact (Lees et al., 2010), resultant in higher ball kicking velocity and hence kicking performance.

From a practical point of view, it must be considered that the PT applied induced general (i.e. jumping, CODS) and soccer-specific (i.e. kicking) explosive adaptations, which may have high transference into game-play performance. Thus, a twice weekly short-term high intensity PT program, implemented as a substitute for some soccer drills within regular in-season soccer practice, can enhance explosive performance in young soccer players compared with soccer training alone, and these improvements can be achieved using 30, 60 or 120 s of rest between plyometric sets. Considering that a shorter rest period will reduce the total training time dedicated to plyometric drills, this will give the chance to redistribute a greater amount of time to exercises needed to maximize performance in young soccer players. Also, it must be considered that although the results of the study demonstrated an increase in explosive ability after PT, it is recommend that this training method should be adequately incorporated in a comprehensive training program that develops the sport-specific abilities that are critical to achieve adequate performance, especially at young ages (early engagement hypothesis) (Ford et al., 2012), and with an adequate aerobic conditioning program to optimize training adaptations.

Although concern has been expressed by some researchers with regard to the injury risk during plyometric training, to the best of the author's knowledge, when adequate controlled plyometric training intervention had been applied, no important injuries had been reported. In fact, plyometric training had been advocated as a preventive injury strategy (Ford et al., 2005; Lephart et al., 2005) and even as a rehabilitation tool (Heiderscheit et al., 1996). It is important to notice that in the present investigation no injuries were reported. More so, although we did not report it on the study, subjects reported (trough an VAS) little subjective muscle pain (between 0 and 2 in a 10 point scale) from their lower extremitis muscles immediately after, 24h, 48h, 72h, and 96h after the first session of the first and last week of training.

Conclusion

In conclusion, G30, G60 and G120 groups achieved similar improvements in explosive performance after training. Therefore, when PT sets are prescribed, 30, 60 or 120 s of rest between these is adequate to induce significant explosive adaptations in young male soccer players.

References

Abdessemed, D., Duche, P., Hautier, C., Poumarat, G. and Bedu, M. (1999) Effect of recovery duration on muscular power and blood lactate during the bench press exercise. *International Journal of Sports Medicine,* **20(6),** 368-73.

Abt, G., Siegler, J. C., Akubat, I. and Castagna, C. (2011) The effects of a constant sprint-to-rest ratio and recovery mode on repeated sprint performance. *The Journal of Strength and Conditioning Research,* **25(6),** 1695-702.

ACSM (2009) American college of sports medicine position stand. Progression models in resistance training for healthy adults. *Medicine and Science in Sports and Exercise,* **41(3),** 687-708.

Balsom, P. D., Seger, J. Y., Sjodin, B. and Ekblom, B. (1992) Maximal-intensity intermittent exercise: Effect of recovery duration. *International Journal of Sports Medicine,* 13(7)**,** 528-33.

Ball, K. (2009) Use of weighted balls for improving kicking for distance, in: Reylly, T. and Kurkusuz, F. (Eds) *Science and football. Proceedings of the sixth world congress on science and football.* London, 285-289.

Bogdanis, G. C., Nevill, M. E., Lakomy, H. K., Graham, C. M. and Louis, G. (1996) Effects of active recovery on power output during repeated maximal sprint cycling. *European Journal of Appliedd Physiology and Occupational Physiology,* **74(5),** 461-9.

Buchheit, M., Mendez-Villanueva, A., Delhomel, G., Brughelli, M. and Ahmaidi, S. (2010) Improving repeated sprint ability in young elite soccer players: Repeated shuttle sprints vs. Explosive strength training. *The Journal of Strength and Conditioning Research,* **24(10),** 2715-22.

Campillo, R. R., Andrade, D. C. and Izquierdo, M. (2012) Effects of plyometric training volume and training surface on explosive strength. *The Journal of Strength and Conditioning Research*. In press.

Cronin, J. B. and Hansen, K. T. (2005) Strength and power predictors of sports speed. *The Journal of Strength and Conditioning Research,* **19(2),** 349-57.

Chaouachi, A., Haddad, M., Castagna, C., Wong Del, P., Kaouech, F., Chamari, K. and Behm, D. G. (2011) Potentiation and recovery following low- and high-speed isokinetic contractions in boys. *Pediatric Exercise Sciences,* **23(1),** 136-50.

Chelly, M. S., Fathloun, M., Cherif, N., Ben Amar, M., Tabka, Z. and Van Praagh, E. (2009) Effects of a back squat training program on leg power, jump, and sprint performances in junior soccer players. *The Journal of Strength and Conditioning Research,* **23(8),** 2241-2249.

De Salles, B. F., Simao, R., Miranda, F., Novaes Jda, S., Lemos, A. and Willardson, J. M. (2009) Rest interval between sets in strength training. *Sports Medicine,* **39(9),** 765-77.

Diallo, O., Dore, E., Duche, P. and Van Praagh, E. (2001) Effects of plyometric training followed by a reduced training programme on physical performance in prepubescent soccer players. *Journal of Sports Medicine and Physical Fitness,* **41(3),** 342-8.

Eston, R., Byrne, C. and Twist, C. (2003) Muscle function after exercise-induced muscle damage: Considerations for athletic performance in children and adults. *Journal of Exercise Sciences and Fitness,* **1(2),** 85-96.

Faigenbaum, A. D. (2006) Plyometrics for kids: Facts and fallacies. *NSCA's Performance Training Journal,* **5(2),** 13-16.

Falk, B. and Dotan, R. (2006) Child-adult differences in the recovery from high-intensity exercise. *Exercise and Sport Science Reviews,* **34(3),** 107-12.

Faude, O., Koch, T. and Meyer, T. (2012) Straight sprinting is the most frequent action in goal situations in professional football. *Journal of Sports Sciences,* **30(7),** 625-31.

FIFA (2012) *Laws of the game 2012/2013,* Zurich, Switzerland, Federation Internationale de Football Association. International Football Association Board.

Ford, K. R., Myer, G. D., Smith, R. L., Byrnes, R. N., Dopirak, S. E. and Hewett, T. E. (2005) Use of an overhead goal alters vertical jump performance and biomechanics. *The Journal of Strength and Conditioning Research,* **19(2),** 394-9.

Ford, P. R., Carling, C., Garces, M., Marques, M., Miguel, C., Farrant, A., Stenling, A., Moreno, J., Le Gall, F., Holmstrom, S., Salmela, J. H. and Williams, M. (2012) The developmental activities of elite soccer players aged under-16 years from brazil, england, france, ghana, mexico, portugal and sweden. *Journal of Sports Sciences*, **30(15),** 1653-63.

Gabbett, T. J., Kelly, J. N. and Sheppard, J. M. (2008) Speed, change of direction speed, and reactive agility of rugby league players. *The Journal of Strength and Conditioning Research*, **22(1),** 174-81.

Garcia-Lopez, D., De Paz, J. A., Moneo, E., Jimenez-Jimenez, R., Bresciani, G. and Izquierdo, M. (2007) Effects of short vs. Long rest period between sets on elbow-flexor muscular endurance during resistance training to failure. *The Journal of Strength and Conditioning Research*, **21(4),** 1320-4.

Gehri, D. J., Ricard, M. D., Kleiner, D. M. and Kirkendall, D. T. (1998) A comparison of plyometric training techniques for improving vertical jump ability and energy production. *The Journal of Strength and Conditioning Research*, **12(2),** 85-89.

Grant, S., Aitchison, T., Henderson, E., Christie, J., Zare, S., Mcmurray, J. and Dargie, H. (1999) A comparison of the reproducibility and the sensitivity to change of visual analogue scales, borg scales, and likert scales in normal subjects during submaximal exercise. *Chest*, **116(5),** 1208-17.

Heiderscheit, B. C., Mclean, K. P. and Davies, G. J. (1996) The effects of isokinetic vs. Plyometric training on the shoulder internal rotators. *Journal of Orthopaedic and Sports Physical Therapy*, **23(2),** 125-33.

Hopkins, W. G., Marshall, S. W., Batterham, A. M. and Hanin, J. (2009) Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, **41(1),** 3-13.

Itoh, K., Ochi, H. and Kitakoji, H. (2008) Effects of tender point acupuncture on delayed onset muscle soreness (doms)--a pragmatic trial. *Chinese Medicine,* **3(14).** doi:10.1186/1749-8546-3-14

Kraemer, W. J., Noble, B. J., Clark, M. J. and Culver, B. W. (1987) Physiologic responses to heavy-resistance exercise with very short rest periods. *International Journal of Sports Medicine,* **8(4),** 247-52.

Kraemer, W. J. and Ratamess, N. A. (2005) Hormonal responses and adaptations to resistance exercise and training. *Sports Medicine,* **35(4),** 339-61.

Le Gall, F., Carling, C., Williams, M. and Reilly, T. (2010) Anthropometric and fitness characteristics of international, professional and amateur male graduate soccer players from an elite youth academy. *Journal of Science and Medicine in Sport,* **13(1),** 90-5.

Lees, A., Asai, T., Andersen, T. B., Nunome, H. and Sterzing, T. (2010) The biomechanics of kicking in soccer: A review. *Journal of Sports Sciences,* **28(8),** 805-17.

Lephart, S. M., Abt, J. P., Ferris, C. M., Sell, T. C., Nagai, T., Myers, J. B. and Irrgang, J. J. (2005) Neuromuscular and biomechanical characteristic changes in high school athletes: A plyometric versus basic resistance program. *British Journal of Sports Medicine,* **39(12),** 932-8.

Lexell, J., Sjostrom, M., Nordlund, A. S. and Taylor, C. C. (1992) Growth and development of human muscle: A quantitative morphological study of whole vastus lateralis from childhood to adult age. *Muscle Nerve,* **15(3),** 404-9.

Maio Alves, J. M., Rebelo, A. N., Abrantes, C. and Sampaio, J. (2010) Short-term effects of complex and contrast training in soccer players' vertical jump, sprint, and agility abilities. *The Journal of Strength and Conditioning Research,* **24(4),** 936-41.

Marginson, V. and Eston, R. (2001) The relationship between torque and joint angle during knee extension in boys and men. *Journal of Sports Sciences,* **19(11),** 875-80.

Marginson, V., Rowlands, A. V., Gleeson, N. P. and Eston, R. G. (2005) Comparison of the symptoms of exercise-induced muscle damage after an initial and repeated bout of plyometric exercise in men and boys. *Journal of Appliedd Physiology,* **99(3),** 1174-81.

Markovic, G. and Mikulic, P. (2010) Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Medicine,* **40(10),** 859-95.

Meylan, C. and Malatesta, D. (2009) Effects of in-season plyometric training within soccer practice on explosive actions of young players. *The Journal of Strength and Conditioning Research,* **23(9),** 2605-13.

Michailidis, Y., Fatouros, I. G., Primpa, E., Michailidis, C., Avloniti, A., Chatzinikolaou, A., Barbero-Alvarez, J. C., Tsoukas, D., Douroudos, Ii, Draganidis, D., Leontsini, D., Margonis, K., Berberidou, F. and Kambas, A. (2013) Plyometrics' trainability in preadolescent soccer athletes. *The Journal of Strength and Conditioning Research,* **27(1),** 38-49.

Morin, J. B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P. and Lacour, J. R. (2012) Mechanical determinants of 100-m sprint running performance. *European Journal of Appliedd Physiology,* **112(11),** 3921-30.

Negrete, R. and Brophy, J. (2000) The relationship between isokinetic open and closed chain lower extremity strength and functional performance. *Journal of Sport Rehabilitation,* **9(1),** 46-61.

Pincivero, D. M., Gear, W. S., Moyna, N. M. and Robertson, R. J. (1999) The effects of rest interval on quadriceps torque and perceived exertion in healthy males. *Journal of Sports Medicine and Physical Fitness,* **39(4),** 294-9.

Pincivero, D. M., Lephart, S. M. and Karunakara, R. G. (1998) Effects of intrasession rest interval on strength recovery and reliability during high intensity exercise. *The Journal of Strength and Conditioning Research,* **12(3),** 152-156.

Randell, A. D., Cronin, J. B., Keogh, J. W. and Gill, N. D. (2010) Transference of strength and power adaptation to sports performance-horizontal and vertical force production. *Strength and Conditioning Journal,* **32(4),** 100-106.

Read, M. M. and Cisar, C. (2001) The influence of varied rest interval lengths on depth jump performance. *The Journal of Strength and Conditioning Research,* **15(3),** 279-283.

Rubley, M. D., Haase, A. C., Holcomb, W. R., Girouard, T. J. and Tandy, R. D. (2011) The effect of plyometric training on power and kicking distance in female adolescent soccer players. *The Journal of Strength and Conditioning Research,* **25(1),** 129-34.

Saez De Villarreal, E., Requena, B. and Cronin, J. B. (2012) The effects of plyometric training on sprint performance: A meta-analysis. *The Journal of Strength and Conditioning Research,* **26(2),** 575-84.

Saraslanidis, P., Petridou, A., Bogdanis, G. C., Galanis, N., Tsalis, G., Kellis, S. and Mougios, V. (2011) Muscle metabolism and performance improvement after two training programmes of sprint running differing in rest interval duration. *Journal of Sports Sciences,* **29(11),** 1167-74.

Sheppard, J. M. and Young, W. B. (2006) Agility literature review: Classifications, training and testing. *Journal of Sports Sciences,* **24(9),** 919-932.

Stolen, T., Chamari, K., Castagna, C. and Wisloff, U. (2005) Physiology of soccer: An update. *Sports Medicine,* **35(6),** 501-36.

Thomas, K., French, D. and Hayes, P. R. (2009) The effect of two plyometric training techniques on muscular power and agility in youth soccer players. *The Journal of Strength and Conditioning Research,* **23(1),** 332-335.

Tomlin, D. L. and Wenger, H. A. (2001) The relationship between aerobic fitness and recovery from high intensity intermittent exercise. *Sports Medicine,* **31(1),** 1-11.

Tonnessen, E., Shalfawi, S. A., Haugen, T. and Enoksen, E. (2011) The effect of 40-m repeated sprint training on maximum sprinting speed, repeated sprint speed endurance, vertical jump, and aerobic capacity in young elite male soccer players. *The Journal of Strength and Conditioning Research,* **25(9),** 2364-70.

Wathen, D. (1993) Literature review: Explosive/plyometric exercises. *Strength and Conditioning Journal,* **15(3),** 17-19.

Webber, L. M., Byrnes, B. C., Rowland, T. W. and Foster, V. L. (1989) Serum creatine kinase activity and delayed onset muscle soreness in prepubescent children: A preliminary study. *Pediatric Exercise Science,* **1(4),** 351-359.

Weeks, B. K. and Beck, B. R. (2010) The relationship between physical activity and bone during adolescence differs according to sex and biological maturity. *Journal of Osteoporosis.* doi: 10.4061/2010/546593.

Wong, P. L., Chamari, K. and Wisloff, U. (2010) Effects of 12-week on-field combined strength and power training on physical performance among u-14 young soccer players. *The Journal of Strength and Conditioning Research,* **24(3),** 644-52.

Young, W. B., James, R. and Montgomery, I. (2002) Is muscle power related to running speed with changes of direction? *Journal of Sports Medicine and Physical Fitness,* **42(3),** 282-8.

TABLE LIST

Table 1. Subject characteristics at the start of the 7-week period. Data are means (±SD).

Variable	Control (n=15)	G30 (n=13)	G60 (n=14)	G120 (n=12)
Pubic hair Tanner stage	2.4 (1.0)	2.2 (1.0)	2.3 (1.1)	2.3 (1.2)
Genital Tanner stage	2.2 (0.6)	2.4 (0.8)	2.2 (0.6)	2.3 (0.9)
Age (y)	10.1 (2.0)	10.4 (2.0)	10.4 (2.3)	10.3 (2.3)
Height (m)	1.43 (0.1)	1.41 (0.1)	1.41 (0.1)	1.42 (0.1)
Body mass (kg)	39.0 (9.3)	37.0 (7.0)	37.2 (6.1)	38.0 (10.0)
Soccer experience (y)	3.4 (1.6)	3.1 (1.9)	3.6 (1.5)	3.0 (1.3)
Session rating of perceived exertion	369 (180)	328 (201)	343 (166)	378 (159)

G30, G60, and G120: 30 s, 60 s, and 120 s rest interval groups, respectively

Table 2. Anthropometrics and performance variables before and after 7 weeks of plyometric training in young soccer players

Variable	Control group (n=14)	G30 (n=13)	G60 (n=13)	G120 (n=11)
Countermovement jump (cm)				
Before	22.1 (4.9)	22.2 (4.1)	21.9 (2.1)	21.7 (4.4)
After	21.9 (4.7)	24.0 (5.6)[a]	23.9 (3.1)[a]	23.5 (5.4)[a]
Training effect (%)	-0.9 (-1.9, 1.9)	8.1 (1.3, 16.8)	9.1 (1.9, 21.9)	8.5 (1.8, 18.6)
Standardized effect	-0.1 (-0.34, 0.24)	0.49 (0.24, 0.79)*	0.58 (0.29, 0.88)*	0.55 (0.27, 0.82)*
20 cm drop jump reactive strength index (mm/ms)				
Before	0.78 (0.2)	0.77 (0.21)	0.75 (0.2)	0.75 (0.3)
After	0.85 (0.2)	1.03 (0.2)[c]	1.01 (0.2)[c]	1.02 (0.3)[c]
Training effect (%)	8.1 (-14.4, 24.7)	33.2 (14.4, 76.1)	35.3 (15.9, 74.3)	36.6 (14.3, 81.1)
Standardized effect	0.27 (-0.31, 0.59)*	0.81 (0.38, 1.27)**	0.89 (0.48, 1.22)**	0.86 (0.39, 1.33)**
40 cm drop jump reactive strength index (mm/ms)				
Before	0.75 (0.3)	0.74 (0.3)	0.74 (0.2)	0.73 (0.3)
After	0.84 (0.2)	1.03 (0.3)[c]	1.02 (0.3)[c]	1.06 (0.3)[c]
Training effect (%)	12.9 (-9.0, 28.7)	39.0 (8.9, 66.4)	38.9 (9.0, 65.3)	46.4 (15.4, 79.7)
Standardized effect	0.48 (-0.36, 0.72)*	0.86 (0.39, 1.6)**	0.88 (0.29, 1.41)**	0.98 (0.44, 1.51)**
20m (s)				
Before	4.3 (0.3)	4.4 (0.5)	4.3 (0.2)	4.3 (0.4)
After	4.5 (0.4)[a]	4.4 (0.3)	4.3 (0.3)	4.4 (0.4)
Training effect (%)	6.6 (2.9, 9.6)	-1.8 (-3.9, 0.7)	0.3 (-1.2, 1.9)	0.4 (-3.0, 3.3)
Standardized effect	0.65 (0.44, 1.32)**	-0.3 (-0.68, 0.28)*	0.09 (-0.19, 0.33)	0.13 (-0.33, 0.60)
Change of direction speed (s)				
Before	7.4 (0.5)	7.4 (0.6)	7.4 (0.5)	7.4 (0.7)
After	7.3 (0.4)	7.0 (0.4)[a]	7.1 (0.5)[a]	7.0 (0.6)[a]
Training effect (%)	-2.6 (-5.0, 2.5)	-6.5 (-10.9, -2.3)	-5.2 (-9.9, -1.1)	-6.9 (-12.1, -2.4)
Standardized effect	-0.4 (-0.77, 0.45)*	-1.03 (-1.42, -0.4)**	-0.87 (-1.5, -0.29)**	-1.04 (-1.6, -0.49)**
Maximal kicking distance (m)				
Before	20.0 (5.3)	19.7 (7.4)	18.9 (5.0)	19.3 (7.0)
After	20.1 (5.8)	22.0 (8.9)[a]	21.8 (4.1)[a]	21.6 (7.0)[a]
Training effect (%)	1.1 (-2.4, 6.6)	11.3 (2.3, 23.4)	15.0 (2.7, 29.9)	12.6 (4.0, 24.1)
Standardized effect	0.01 (-0.09, 0.21)	0.39 (-0.03, 0.68)*	0.49 (-0.01, 0.88)*	0.43 (0.08, 0.77)*

Before and after values are means (± SD). Training effect and standardized effect values are mean (90% confidence limits). G30, G60, and G120: 30 s, 60 s, and 120 s rest interval groups, respectively; * small standardized effect; ** moderate standardized effect; a, b, c: denote significant difference pre to post training ($p<0.05$, $p<0.01$ and $p<0.001$, respectively).

KEY POINTS

Replacing some soccer drills by low volume high-intensity plyometric training would be beneficial in jumping, change of direction speed, and kicking ability in young soccer players.

A rest period of 30, 60 or 120 seconds between low-volume high-intensity plyometric sets would induce significant and similar explosive adaptations during a short-term training period in young soccer players.

Data from this research can be helpful for soccer trainers in choosing efficient drills and characteristics of between sets recovery programs to enhance performances in young male soccer players.

AUTHORS BIOGRAPHY

RAMIREZ-CAMPILLO R

Employment

Department of Physical Activity Sciences, University of Los Lagos, Osorno, Chile.

Degree

MSc

Research interests

Exercise physiology, training

E-mail: r.ramirez@ulagos.cl

ANDRADE DC

Employement

Biomedical Department, Faculty of Health Science, Universidad de Antofagasta, Antofagasta, Chile.

Degree

BSc

Research interests

Exercise physiology, plyometric training , baroreflex.

e-mail

david.andrade@uantof.cl

ÁLVAREZ C

Employment

Family Health Center of Los Lagos, Health Promotion Program, Los Lagos, Chile

Degree

MSc

Research interests

Exercise physiology, training

E-mail: profecristian.alvarez@gmail.com

HENRÍQUEZ-OLGUÍN C

Employment

Sport Sciences Laboratory, MEDS Clinic, Santiago (Chile).

Degree

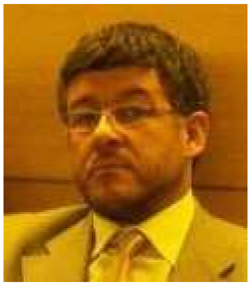
MSc

Research interests

Exercise physiology, muscle adaptation

E-mail: carlos.henriquez@meds.cl

MARTÍNEZ C



Employement

Physical Education Department, University of La Frontera, Temuco, Chile

Degree

MSc

Research interests

Exercise physiology, training

E-mail: cmartin@ufro.cl

BÁEZ EI

Employement

Department of Sport and Recreation, University of Playa Ancha, Valparaíso, Chile

Degree

MSc

Research interests

Exercise physiology, training, combat sports

E-mail: eduardo.baez@upla.cl

SILVA-URRA J

Employement

Biomedical Department, Faculty of Health Sciences, Laboratory of Exercise Physiology and Medicine at Altitude, Antofagasta University (Chile)

Degree

MD, MSc

Research interests

Exercise physiology, training

E-mail: silvaurra@uantof.cl

BURGOS CH

Employement

Sciences of exercise Laboratory, Clinica MEDS

Degree

MSc

Research interests

Exercise physiology, training

E-mail: burgoschile@hotmail.com

IZQUIERDO M

Employement

Public University of Navarre, Department of Health Sciences, Spain

Degree

PhD

Research interests

Exercise physiology, training,

E-mail: mikel.izquierdo@gmail.com