

1 **The effect of varying plyometric volume on stretch-shortening cycle capability in**
2 **collegiate male rugby players**

3 Running Title: Plyometric training volume

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1 ABSTRACT

2 The purpose of this study was to identify the effectiveness of low and high volume
3 plyometric loads on developing stretch shortening cycle capability in collegiate rugby
4 players. A between- group repeated measures design was used. Thirty six subjects (age 20.3
5 ± 1.6 yrs, mass 91.63 ± 10.36 kg, stature 182.03 ± 5.24 cm) were randomly assigned to one of
6 three groups, a control group (CG), a low volume plyometric group (LPG) or a high volume
7 plyometric group (HPG). Data were collected from a force plate, and measures of reactive
8 strength index (RSI) and leg stiffness were calculated from jump height, contact time and
9 flight time. A significant between group \times time ($F = 4.01$, $P < 0.05$) interaction effect for RSI
10 was observed. Bonferroni post hoc analysis indicated that both the LPG training group ($P =$
11 0.002) and HPG training group ($P = 0.009$) were significantly higher than the control group.
12 No significant interaction effect between time \times group were observed for leg stiffness ($F =$
13 1.39 , $P = 0.25$). The current study has demonstrated that it is possible to improve reactive
14 strength capabilities via the use of a low volume plyometric program. The low volume
15 program elicited the same performance improvement in RSI as a high volume program whilst
16 undertaking a lower dose. This suggests that strength and conditioning coaches may be able
17 to benefit from the ability to develop more time efficient and effective plyometric programs.

18 **Keywords:** training, reactive strength, leg stiffness

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1 INTRODUCTION

2 The stretch-shortening cycle (SSC) is a naturally occurring muscle function whereby a
3 muscle is stretched and this is immediately followed by a concentric action of the same
4 muscle. The SSC can be found in common movements such as running, jumping and
5 hopping. When a concentric action of the muscle immediately follows an eccentric action,
6 then the concentric action is more powerful than when the shortening action occurs on its
7 own (10, 23). Efficient SSC movements can not only result in a more powerful propulsive
8 force, but can also lead to energy conservation and an athlete can reduce the metabolic costs
9 of such a movement (29).

10 It is clear that the increased propulsive force and reduction of metabolic costs would be
11 advantageous when training for sports performance. One of the most common modalities for
12 training the SSC is via the use of plyometrics (9) relying on powerful, quick movements
13 which utilize the SSC (27). Plyometric exercises enable a muscle to attain maximal external
14 force in a very short time, (2) and utilize the increased power developed by the SSC (4).
15 Literature has demonstrated that plyometric training can be used to improve agility, running
16 economy and power output (10, 11), as well as strength, coordination and possible reduction
17 of injuries (7).

18 There are a number of methods to determine SSC function using field based measures.
19 Rebound jump testing can provide information on the reactive strength index (RSI) and leg
20 stiffness. RSI represents maximal activities requiring the utilization of the SSC actions (21),
21 and is calculated by dividing the height jumped by the time spent in contact with the ground
22 when developing force (9). Leg stiffness is the most common representation of SSC muscle
23 action as it represents the spring-mass model that characterizes the biomechanical properties
24 of whole-body SSC actions (22), particularly during rapid movements such as decelerations
25 and change of direction experienced during field based running sports (24, 25, 26).

1 It has been demonstrated that one of the physiological properties to be altered following
2 plyometric training is musculotendinous stiffness (5). Although this benefit has been
3 demonstrated to be due to plyometric training, there are a number of factors that may affect
4 the success of a plyometrics program, including age, gender and training history (7). Saez de
5 Villareal et al. (7) also point out that research studies have differed in terms of duration,
6 volume and intensity within their studies and as such there is still a lack of clarity as to the
7 optimal levels and combinations of these factors to achieve maximum performance.

8 It has been shown that both low and moderate plyometric training frequencies (420 and 840
9 total jumps) produced greater jumping and sprinting gains than a high frequency (1680 total
10 jumps) of plyometric training program (8). Further, a meta-analysis of 56 plyometric studies,
11 which included training programs of more than 10 weeks consisting of more than 20 sessions
12 with more than 50 jumps per session were evidenced to maximize the probability of obtaining
13 significantly greater improvements in performance (7).

14 It has been identified that strength and conditioning coaches working with rugby football
15 players face two main challenges: Firstly, to provide appropriate metabolic conditioning in
16 the most time-efficient manner; secondly, to develop and maintain high levels of strength and
17 power while athletes are concurrently performing high volumes of metabolic training and
18 team practices (12). It is therefore important that training programs are designed to be as time
19 efficient as possible. The purpose of this study was to determine the effects of low and high
20 volume plyometric programs on improvements in reactive strength and leg stiffness. It is
21 suggested that if low plyometric volumes are as effective as high volume plyometric
22 programs then this will be more time efficient and therefore very beneficial to the strength
23 and conditioning coach. Therefore, the aim of the proposed study is to identify whether
24 similar performance benefits are gained from a low volume plyometric program and a high
25 volume plyometric program for rugby populations. It was hypothesized that both the low and

1 high plyometric training programs would improve subjects' SSC muscle actions, with the
2 magnitude of change in RSI and leg stiffness being similar between the two training groups.

3 **METHODS**

4 *Experimental Approach to the Problem*

5 The experiment was carried out utilizing a between- group, repeated measures design to
6 examine the effect of different plyometric volumes on measures of SSC in collegiate rugby
7 players. The subjects were randomly assigned to one of three groups, a control group (CG), a
8 low volume plyometric group (LPG) and a high volume plyometric group (HPG). Data were
9 collected from a force plate, and measures of RSI and leg stiffness were calculated from jump
10 height, contact time and flight time data. The estimation of sample size for the study was
11 calculated using data collected from an initial pilot study. 10 male subjects (age 20.4 ± 0.8 yr;
12 stature 1.86 ± 0.09 m and body mass 86.3 ± 15.2 kg) took part in the reliability study. Subjects
13 undertook testing during two separate sessions (test – retest) which were held one week apart
14 to ascertain the reliability of the force plate measuring RSI:

$$16 \quad \text{RSI CV} = 6.1\%$$

17
18 Where CV refers to the coefficient of variation, and SWC refers to the smallest worthwhile
19 change. The smallest worthwhile change was calculated as a factor of 0.2 of the between-
20 subject standard deviation (15).

$$22 \quad \text{Sample size} = 8 * (\text{CV}^2 / \text{SWC}^2)$$

23 According to the data, the calculated group size was seven subjects per group.

25 *Subjects*

1 Thirty six male collegiate rugby union players aged 20.3 ± 1.6 yrs, body mass 91.63 ± 10.36
2 kg, stature 1.82 ± 0.05 m, with 1- 2 years history of plyometric training, volunteered to
3 participate in the study. The subjects were randomly assigned to one of three groups, a
4 control group (CG), a low volume plyometric group (LPG), or a high volume plyometric
5 group (HPG). Subjects were counterbalanced within each group, to ensure equal splits of
6 forwards and backs. Subjects were required to attend at least 80% of the training sessions in
7 order to be included in the final analysis of the study. Following the completion of the
8 training program, 29 subjects qualified for inclusion for the final analysis from the three
9 different groups: LPG (n = 10), HPG (n = 9) and control (n = 10). None of the subjects
10 reported an injury at the time of testing. The project received ethical approval by the
11 University's Research Ethics committee, and subjects completed both a subject consent and
12 physical activity readiness questionnaire (PARQ) which were obtained prior to testing.
13 Subject confidentiality was upheld with any information and data being kept in accordance
14 with the Data Protection Act (1998), and subject anonymity was maintained at all times.
15 Subject identification was only known by the principal researcher and the supervisory team.

16 *Procedures*

17 Subjects attended two familiarisation sessions prior to the initial testing procedure. These
18 sessions took place two weeks prior to the testing at the same time and place that the testing
19 occurred. The familiarisation sessions included all techniques that would be used during the
20 testing sessions. Subjects were also allowed practice attempts at all techniques as part of the
21 warm up immediately prior to testing. Throughout the familiarisation, subjects were
22 encouraged to minimize contact with the ground and maximize height. Testing was
23 completed at the same time on each of the testing days at the same indoor venue. Testing was
24 carried out by the same tester. All subjects were asked to refrain from eating, drinking or
25 taking part in any physical activity for up to one hour before testing. All subjects were also

1 asked to wear the same footwear and clothing for all testing and training sessions. Testing
2 included drop jumps from 30cm, 45cm, and 60cm along with two footed hopping.

3

4 All jump tests were performed on a 900 mm x 600 mm force platform (type 9287BA, Kistler
5 Instrumente AG, Winterthur, Switzerland) fitted with an integrated charge amplifier. All
6 output data was automatically captured on a PC, at a sampling rate of 1000Hz and saved in
7 the Bioware software package) (Bioware® V.3.2.6). For all jump tests, subjects were
8 encouraged to jump as high as possible, whilst minimising ground contact time. Three trials
9 of each drop jump were performed during the testing sessions, with the best score being used
10 for data analysis (3). For the repeated jumps, 10 jumps were completed and the middle 6 were
11 recorded and used for analysis.

12

13 *Reactive Strength Index:*

14 RSI was measured using a drop jump, performed starting from a standing position, with the
15 hands placed on the hips. Subjects stepped off the box with one foot, landing with two feet
16 simultaneously onto the force plate. As contact was made with the force plate subjects
17 immediately performed a vertical jump. The drop jumps were carried out at heights of 30cm,
18 45cm and 60cm (30). Subjects were given three trials at each height with the best trial being
19 used for analysis (3). RSI was calculated by dividing jump height (mm) by contact time (ms)
20 (18).

21

$$\text{Jump height} = (\text{flight time}^2 \times \text{gravity})/8$$

22

$$\text{RSI} = \text{jump height (mm)} / \text{ground contact time (ms)}$$

23

Leg Stiffness:

1 Leg stiffness was measured via the use of double leg rebound jumps (hops). The double-leg
 2 10 multiple hops were performed starting from a standing position. Subjects performed a
 3 series of 10 hops at a frequency that was self selected by the subject (14, 26). During the
 4 hopping tests, subjects were instructed to hop with their torso's upright and their hands on
 5 their hips (13) and encouraged to maximize the rigidity in their lower limbs and minimize the
 6 ground contact time (18). Leg stiffness ($\text{kN}\cdot\text{m}^{-1}$) was calculated from force plate data using
 7 the average ground contact times and flight times across the middle 6 rebound jumps (jumps
 8 3 – 8), together with body mass, using the equation of Dalleau et al. (2004):(6).

$$9 \quad \text{Leg Stiffness } (K_N) = M * \pi(T_f + T_c) / T_c^2 ((T_f + T_c / \pi) - (T_c / 4)) \quad (19)$$

10 Where K_N refers to leg stiffness, M is the total body mass, T_c is equal to ground contact time
 11 and T_f represents the flight time.

12 *Training intervention*

13 The study involved a 6 week plyometric training program for both experimental groups,
 14 which reflects the training protocol durations reported elsewhere in the literature (1, 20, 27,
 15 28). The 6 week program formed part of the club's periodized training program. The sessions
 16 took place on an indoor surface and were delivered alongside the normal club strength and
 17 conditioning program. Total training time was determined by the intensity of the sessions and
 18 the need for subjects to be recovered between sets, with more rest provided for those
 19 exercises that elicited greater eccentric loading (17). At least 48 hours was planned between
 20 each plyometric group to allow for relevant recovery. The sessions consisted of a range of
 21 plyometric drills which included drop jumps, lateral and horizontal jumps, hurdle jumps and
 22 bounds (Table 1). The drop jump height was individually prescribed based on the optimal
 23 drop jump height identified during the initial testing phase (the height where the RSI score
 24 was equalled or bettered). Verbal feedback was provided during each session which was

1 aimed at minimising contact time and increasing flight time wherever possible. Feedback was
2 also provided in relation to any postural or technical issues although this was minimal as each
3 subject had 1 – 2 years of plyometric training history. The control group undertook their
4 regular club strength and conditioning training of two sessions a week along with the regular
5 in season program of games and skill based training, but did not undertake any plyometric
6 based training during the duration of the study.

7
8 *****Insert Table 1 near here*****
9

10 **Statistical Analyses**

11 Descriptive statistics (mean \pm SD) for the different variables were calculated. The training
12 related effects were assessed via a between-group repeated measures analysis of variance
13 (ANOVA). For RSI a $3 \times 2 \times 3$ RM ANOVA was performed where drop height, trial and
14 group were the measured variables (group \times trial \times height). Drop height refers to the 30cm,
15 45cm and 60cm heights used for both the pre and post testing, trial refers to the pre and post
16 tests, and the group refers to the Control group, HPG or LPG. For leg stiffness a 3×2 RM
17 ANOVA was utilized where group and time were the measured variables (group \times trial),
18 where group refers to the Control group, HPG or LPG and trial refers to pre or post testing.
19 Mauchly's test was used to test for sphericity of the data and where it was violated a Huynh-
20 Feldt adjustment was utilized. Levene's test was used to assess the equality of variances
21 within the samples. A Bonferroni analysis was used for all post hoc analysis. Three trials of
22 each jump were performed during the testing sessions, with the best score being used for RSI
23 data analysis. The middle 6 rebound jumps (jumps 3 – 8) were used to analyse leg stiffness.
24 The classification of effect sizes was determined by Cohen's *d*. The effect size was classified

1 as trivial ($0.00 \leq d \leq 0.49$), moderate ($0.50 \leq d \leq 0.79$), and large ($d \geq 0.80$). All statistical
2 analysis was carried out via SPSS® (Chicago, Illinois).

3 RESULTS

4 Means (\pm SD) for reactive strength index for each group are shown in Table 2. Mauchly's test
5 indicated that the assumption of sphericity had been violated for the main effects of trial \times
6 height, $\chi^2(2) = 10.74$, $P < 0.01$. Therefore degrees of freedom were corrected using Huynh
7 Feldt estimates of sphericity ($\epsilon = .84$ for the main effect of trial \times height).

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

9
10 A significant interaction effect (group \times time) was evidenced for measures of RSI ($F = 4.01$,
11 $P < 0.05$). Bonferroni post hoc analysis indicated that the LPG training group demonstrated a
12 significant difference ($P = 0.002$) from the control group, whilst the HPG training group ($P =$
13 0.009) also demonstrated a significant difference from the control group. However, there was
14 no significant difference between those in the LPG training group and the HPG training
15 group. (Table 2).

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

17
18 No significant interaction effects (trial \times group) or main effects were observed for measures of
19 leg stiffness ($F = 1.39$, $P = 0.25$), all groups showed increases in post testing values, with
20 trivial effect sizes demonstrated for the LPG (0.06) and control groups (0.08), and a moderate
21 effect size (0.54) shown for HPG measures.

22 23 DISCUSSION

1 The aim of the study was to identify whether similar SSC performance benefits are evident
2 from a low volume plyometric program or a high volume plyometric program. Results
3 demonstrate that changes in RSI in both LPG and HPG groups were significantly difference
4 compared to the CON group. Further, the results indicate that a low volume plyometric
5 program produces similar performance enhancements in terms of RSI as a high volume
6 program, supporting the study's hypothesis. No significant changes were evident for leg
7 stiffness in either experimental group compared to the CON group.

8 As the RSI is a measure of SSC capability and more importantly being efficient at
9 overcoming eccentric forces (10), it can be proposed that the subjects in both the HPG and
10 LPG groups will have increased their SSC capabilities. There are a number of potential
11 contributing factors to this change in function and may include; increased neural excitation
12 before the concentric action, giving a greater potentiation effect, increased utilisation of
13 stored elastic energy in the musculotendinous unit, a desensitisation of the Golgi-tendon
14 organ's inhibitory response and an increase in the reflex contributions of the muscle spindles
15 (10). However it is beyond the scope of this study to ascertain the mechanism of the change
16 for this population and training program. The LPG group had a smaller standard deviation
17 which suggests that subjects in the group were eliciting similar training effects, whilst the
18 larger standard deviation found within the HPG groups suggests that there are larger
19 individual differences within the group. Interestingly the control group showed a stable score
20 in RSI across the study period, despite it being lower than the two training groups across both
21 baseline and post intervention measures. This would indicate that exposure to only rugby
22 specific strength and conditioning training maybe sufficient to maintain but not improve RSI.
23 The results of the training interventions suggests that the same or better training effect can be
24 accomplished with a low volume training program as with a high volume training program
25 (480 contacts vs. 1920 contacts), and with greater variability in the training response of the

1 HPG. These data are aligned with a study indicated that a low (420 total contacts) and
2 moderate (840 contacts) frequency plyometric program produced greater jumping and
3 sprinting gains than a high (1680 contacts) frequency program (8). However it must be
4 identified here that the focus of Saez de Villareal et al (7) study was frequency of sessions
5 rather than volume of sessions completed and that the training program consisted only of
6 drop jumps which may have limited ecological validity to many practitioners.

7 A meta- analysis evidenced that to maximize any potential significant training effects on
8 measures of RSI, plyometric programs should be designed to include volumes of more than
9 10 weeks, with at least 20 sessions and with at least 50 jumps of a high intensity nature in
10 each session (7). The analysis reported a 3.2cm increase in SJ and an 2.9cm increase in CMJ
11 (7). This led the authors to state that plyometric training is effective in improving the vertical
12 jump height (7% increases). The current study would seem to induce similar changes with
13 just fewer than 50% of the suggested minimum contacts. Previous research has indicated that
14 it takes 4 months of plyometric training to inhibit the Golgi-tendon organ and utilize the
15 potentiation caused by the activation of muscle spindles (29). The results obtained for RSI are
16 somewhat interesting in that they also show that the temporal pattern of increased SSC
17 muscle actions is more rapid than literature suggests. This suggests that the results of this
18 study could be of significant practical importance to strength and conditioning coaches, when
19 looking to plan effective and efficient training programs.

20 Results revealed that there were no significant increases in leg stiffness as a result of the HPG
21 or LPG, although the results did demonstrate a moderate (0.54) and small (0.06) effect size
22 for both experimental groups respectively. Although this improvement exists, further analysis
23 of the data reveals that the response to the training programs was found to be individualized
24 with some subjects increasing considerably, whilst others demonstrated no improvement and
25 some even showed a decrement in their performance levels. This result is supported by a

1 recent study that implemented a fatigue protocol, evidencing that some participants showed
2 improvement whilst others demonstrated no increase or even a decrease in stiffness
3 performance (25).

4 It may be seen as somewhat surprising that as leg stiffness is so closely linked to SSC
5 function (24) that subjects in both experimental groups saw a significant increase in
6 performance of RSI values whilst no significant increases were detected in leg stiffness.
7 However, there are some contributory factors that may help to explain the lack of significant
8 improvement. Examination of the scientific literature shows that care needs to be taken when
9 interpreting results as leg stiffness is modulated depending on the specific demands of any
10 particular task (31). Also movements that vary kinematically, even slightly, may engender
11 significant differences in leg stiffness.

12 Modulation of leg stiffness adjustment for a range of hopping frequencies, has been identified
13 that as hopping frequencies increased then leg stiffness increased (13). Whilst undertaking
14 both the testing and the training program, all movements were carried out at the preferred
15 frequency of the subject and so they may not have had the opportunity to carry out
16 movements where a potential increase in leg stiffness occurred.

17 Within the same study, the authors also identified that the increase in leg stiffness was mainly
18 due to the decrease in vertical displacement of the centre of mass (COM). They propose that
19 as the hopping frequency increases, the stiffness of the spring-mass system increases and the
20 displacement of the COM decreases so that contact time is minimized and the ability is
21 created to bounce off the ground in less time. Within the training program, whilst subjects
22 were encouraged to minimize contact time and jump as high as possible, there was no
23 particular attention paid to the amount of COM displacement and as a result, this may have
24 had an impact on the stiffness developed within the training sessions.

1 A recent study on leg stiffness in hopping, with subjects to selecting their own hopping
2 frequency, suggests that subjects accommodate their hopping frequency in order to maintain
3 their leg stiffness despite any increase in hopping intensity (16). They go on to suggest that
4 adjustments may occur in what seems to be similar hopping conditions and that subjects
5 prefer to select an 'optimal' leg stiffness which is independent of differences in hopping
6 intensity, where frequency of hopping is not a constraint. This suggests that even within the
7 testing conditions carried out within the present study, subjects could select their 'optimum'
8 stiffness based on the fact that they were able to hop at their preferred frequency.

9 PRACTICAL APPLICATIONS

10 From the results of the current study, it can be suggested that a low volume plyometric
11 program produces similar performance enhancements in terms of reactive strength as a high
12 volume program, yet with a greater efficiency (25% of the total for HPG). The results would
13 also suggest that increasing the number of contacts within a program would not necessarily
14 lead to an increase in reactive strength capabilities in collegiate rugby players with 1-2 years
15 training history. The results would also support the suggestion of de Villarreal et al. (8) and
16 Sankey et al. (27), that there may be a minimal training threshold required to gain a
17 significant performance improvement and after which further training is no longer
18 advantageous. However, the practical applications of this study would only apply to athletes
19 with limited plyometric training experience. These results may not be the same in individuals
20 with either a lower or higher training age and more research is needed to understand the dose-
21 response relationship in different populations

REFERENCES

1. Adams K, O'Shea JP, O'Shea KL, and Climstein M. The Effect of Six Weeks of Squat, Plyometric and Squat-Plyometric Training on Power Production. *The Journal of Strength & Conditioning Research* 6: 36-41, 1992.
2. Brewer C. Strength and conditioning for games players. *Coachwise Business Solutions*, 2005.
3. Castagna C, Chaouachi A, Rampinini E, Chamari K, and Impellizzeri F. Aerobic and explosive power performance of elite Italian regional-level basketball players. *The Journal of Strength & Conditioning Research* 23: 1982-1987, 2009.
4. Chandler TJ and Brown LE. Conditioning for strength and human performance. *Lippincott Williams & Wilkins*, 2008.
5. Cornu C, Silveira M-IA, and Goubel F. Influence of plyometric training on the mechanical impedance of the human ankle joint. *European journal of applied physiology and occupational physiology* 76: 282-288, 1997.
6. Dalleau G, Belli A, Viale F, Lacour J, and Bourdin M. A simple method for field measurements of leg stiffness in hopping. *Int J Sports Med* 25: 170-176, 2004.
7. de Villarreal ES-S, Kellis E, Kraemer WJ, and Izquierdo M. Determining variables of plyometric training for improving vertical jump height performance: a meta-analysis. *The Journal of Strength & Conditioning Research* 23: 495-506, 2009.
8. de Villarreal ESS, González-Badillo JJ, and Izquierdo M. Low and moderate plyometric training frequency produces greater jumping and sprinting gains compared with high frequency. *The Journal of Strength & Conditioning Research* 22: 715-725, 2008.
9. Dodd DJ and Alvar BA. Analysis of acute explosive training modalities to improve lower-body power in baseball players. *The Journal of Strength & Conditioning Research* 21: 1177-1182, 2007.
10. Flanagan EP and Comyns TM. The use of contact time and the reactive strength index to optimize fast stretch-shortening cycle training. *Strength & Conditioning Journal* 30: 32-38, 2008.
11. Flanagan EP and Harrison AJ. Muscle dynamics differences between legs in healthy adults. *The Journal of Strength & Conditioning Research* 21: 67-72, 2007.

- 1 12. Gamble P. Physical Preparation for Elite-Level Rugby Union Football. *Strength &*
2 *Conditioning Journal* 26: 10-23, 2004.
- 3 13. Hobara H, Inoue K, Muraoka T, Omuro K, Sakamoto M, and Kanosue K. Leg
4 stiffness adjustment for a range of hopping frequencies in humans. *Journal of*
5 *Biomechanics* 43: 506-511, 2010.
- 6 14. Hobara H, Kanosue K, and Suzuki S. Changes in muscle activity with increase in leg
7 stiffness during hopping. *Neuroscience letters* 418: 55-59, 2007.
- 8 15. Hopkins WG. Sample sizes for magnitude-based inferences about clinical, practical or
9 mechanistic significance. *Medicine and Science in Sports and Exercise* 38, 2006.
- 10 16. Kuitunen S, Ogiso K, and Komi P. Leg and joint stiffness in human hopping.
11 *Scandinavian Journal of Medicine & Science in Sports* 21: e159-e167, 2011.
- 12 17. Lloyd RS, Meyers RW, and Oliver JL. The natural development and trainability of
13 plyometric ability during childhood. *Strength & Conditioning Journal* 33: 23-32,
14 2011.
- 15 18. Lloyd RS, Oliver JL, Hughes MG, and Williams CA. Reliability and validity of field-
16 based measures of leg stiffness and reactive strength index in youths. *Journal of*
17 *Sports Sciences* 27: 1565-1573, 2009.
- 18 19. Lloyd RS, Oliver JL, Hughes MG, and Williams CA. The effects of 4-weeks of
19 plyometric training on reactive strength index and leg stiffness in male youths. *The*
20 *Journal of Strength & Conditioning Research* 26: 2812-2819, 2012.
- 21 20. Makaruk H and Sacewicz T. Effects of plyometric training on maximal power output
22 and jumping ability. *Human Movement* 11: 17-22, 2010.
- 23 21. McClymont D. Use of the reactive strength index (RSI) as an indicator of plyometric
24 training conditions. Presented at Science and Football V: The proceedings of the fifth
25 World Congress on Sports Science and Football, Lisbon, Portugal, 2005.
- 26 22. McMahon TA and Cheng GC. The mechanics of running: how does stiffness couple
27 with speed? *Journal of biomechanics* 23: 65-78, 1990.
- 28 23. Nicol C, Avela J, and Komi PV. The stretch-shortening cycle. *Sports Medicine* 36:
29 977-999, 2006.
- 30 24. Oliver J and Smith PM. Neural control of leg stiffness during hopping in boys and
31 men. *Journal of Electromyography and Kinesiology* 20: 973-979, 2010.
- 32 25. Oliver JL, Croix MBDS, Lloyd RS, and Williams CA. Altered neuromuscular control
33 of leg stiffness following soccer-specific exercise. *European Journal of Applied*
34 *Physiology* 114: 2241-2249, 2014.

- 1 26. Padua DA, Carcia CR, Arnold BL, and Granata KP. Gender differences in leg
2 stiffness and stiffness recruitment strategy during two-legged hopping. *Journal of*
3 *Motor Behavior* 37: 111-126, 2005.
- 4 27. Sankey SP, Jones PA, and Bampouras T. Effects of two plyometric training
5 programmes of different intensity on vertical jump performance in high school
6 athletes. *Serbian Journal of Sports Sciences* 2: 123-130, 2008.
- 7 28. Turner AM, Owings M, and Schwane JA. Improvement in running economy after 6
8 weeks of plyometric training. *The Journal of Strength & Conditioning Research* 17:
9 60-67, 2003.
- 10 29. Turner AN and Jeffreys I. The stretch-shortening cycle: Proposed mechanisms and
11 methods for enhancement. *Strength & Conditioning Journal* 32: 87-99, 2010.
- 12 30. Wallace BJ, Kernozek TW, White JM, Kline DE, Wright GA, Peng H-T, and Huang
13 C-F. Quantification of vertical ground reaction forces of popular bilateral plyometric
14 exercises. *The Journal of Strength & Conditioning Research* 24: 207-212, 2010.
- 15 31. Wilson JM and Flanagan EP. The role of elastic energy in activities with high force
16 and power requirements: a brief review. *The Journal of Strength & Conditioning*
17 *Research* 22: 1705-1715, 2008.

1 Legends to tables

2 Table 1: Low and High Volume Plyometric Group Training Program

3

4 Table 2: Mean (\pm SD) for reactive strength index during drop jumps

5

6 Table 3: Mean (\pm SD) Leg Stiffness Values

7

8

9

ACCEPTED

1 Table 1: Low and High Volume Plyometric Group Training Program
2

		LPG	HPG
Week	Exercises	Repetitions	Repetitions
1	Standing vertical jumps (tuck jumps)	1 x 10	4 x 10
	Multiple two-foot hurdle jumps	2 x 5	8 x 5
	Repeated 2 foot jumps (horizontal)	2 x 5	8 x 5
	Alternate leg bound	2 x 5	8 x 5
2	Standing vertical jumps (tuck jumps)	1 x 10	4 x 10
	Multiple two-foot hurdle jumps	2 x 5	8 x 5
	Repeated 2 foot jumps (horizontal)	2 x 5	8 x 5
	Alternate leg bound	2 x 5	8 x 5
3	Lateral two foot jumps	1 x 10	4 x 10
	Multiple two-foot hurdle jumps	2 x 5	8 x 5
	Single foot hops	2 x 5	8 x 5
	Drop Jumps	2 x 5	8 x 5
4	Lateral two foot jumps	1 x 10	4 x 10
	Multiple two-foot hurdle jumps	2 x 5	8 x 5
	Single foot hops	2 x 5	8 x 5
	Drop Jumps	2 x 5	8 x 5
5	Lateral one foot jumps	1 x 10	4 x 10
	Multiple two-foot hurdle jumps	2 x 5	8 x 5
	Drop Jumps	2 x 5	8 x 5
	Single foot drop jumps	2 x 5	8 x 5
6	Lateral one foot jumps	1 x 10	4 x 10
	Multiple two-foot hurdle jumps	2 x 5	8 x 5
	Drop Jumps	2 x 5	8 x 5
	Single foot drop jumps	2 x 5	8 x 5
	Total Foot Contacts	480	1,920

1 Table 2: Mean (\pm SD) for reactive strength index during drop jumps

Group	30cm			45cm			60cm		
	Pre	Post	ES	Pre	Post	ES	Pre	Post	ES
LPG	1.26 \pm 0.35	1.40 \pm 0.30*	0.58	1.33 \pm 0.40	1.45 \pm 0.38*	0.58	1.26 \pm 0.35	1.48 \pm 0.33*	0.54
HPG	1.23 \pm 0.33	1.30 \pm 0.31*	0.38	1.26 \pm 0.36	1.36 \pm 0.38*	0.52	1.25 \pm 0.42	1.37 \pm 0.34*	0.24
CON	0.84 \pm 0.18	0.81 \pm 0.21	-0.15	0.91 \pm 0.24	0.85 \pm 0.22	-0.26	0.83 \pm 0.22	0.87 \pm 0.33	0.14

2 * Statistically significant effect compared to CON ($P < 0.05$).

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2Table 3: Mean (\pm SD) Leg Stiffness Values

Leg Stiffness ($\text{kN}\cdot\text{m}^{-1}$)			
Group	Pre	Post	Effect Size
LPG	35.20 \pm 8.62	36.06 \pm 5.47	0.06
HPG	35.44 \pm 5.82	38.81 \pm 6.63	0.54
CON	34.54 \pm 7.67	35.09 \pm 4.59	0.08

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