# The effect of four weeks of plyometric training on reactive strength index and leg stiffness is sport dependent

Plyometric training effects on reactive strength index and leg stiffness

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## ABSTRACT

BACKGROUND: Plyometric exercises are often used to develop lower limb strength and performance-related biomechanics such as leg stiffness. However, the effectiveness of plyometric training may depend on participants' own training and performance demands. The purpose of this study was to examine the effect of plyometric training on reactive strength index (RSI) and leg stiffness (Kleg) on young athletes of different sports.

METHODS: Forty eight female athletes (25 Taekwondo (TKD) & 23 rhythmic gymnastics (RG), mean ± SD: age: 8.94 ± 2.50 years; mass: 29.73 ± 7.69 kg; height: 138.84 ± 11.90 cm; training experience: 4.62 ± 2.37 years) participated in this study. Participants were randomly assigned to experimental (PT, N = 24) and control (CG, N = 24) groups. The PT group followed a twice-weekly plyometric training program for 4 weeks. Plyometric drills lasted approximately 5–10 s, and at least 90 s rest was allowed after each set. To examine RSI, participants performed trials of five maximal CMJs. Submaximal hopping (20 hops) was performed in order to examine leg stiffness.

RESULTS: Significant interaction effect was found for RSI and the post hoc analysis showed that RSI significantly increased by 35% ($p = 0.017$) in RG athletes, whereas a significantly reduction by 28% ($p = 0.004$) was revealed in TKD athletes. The interaction effect between time and group was statistically significant for Kleg ($p < 0.05$) with Kleg significantly increasing by 31% ($p = 0.008$) in TKD athletes, but remaining unchanged ($p > .05$) in RG athletes.

CONCLUSIONS: The results showed that the effect of a 4-week plyometric training program on RSI and leg stiffness is sport dependent. Further, the applied plyometric program was effective in reducing ground contact time and therefore increasing leg stiffness.


**Key words:** plyometric exercise, rhythmic gymnastics, Taekwondo, athletes

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## Introduction

Plyometric exercises (PE) of the lower limbs such as jumping, bounding, and hopping aim to improve the muscle force and power production due to the stretch shortening cycle (SSC) of the muscle unit.[1, 2] The main feature of PE is the ability to efficiently use the SSC to maximize power production.[3] The SSC is characterized by a rapid transition between the initial eccentric "stretch" and subsequent concentric "recoil".[4] During SSC exercises the muscular contraction produced is a more powerful contraction than that which would result from a concentric action alone,[5] allowing higher forces to be produced at all velocities during the concentric phase.[6] Typically, PEs involve exercises such as vertical jumps and box jumps to train the slow SSC or bounding, repeated hurdle hops and depth jumps to train the fast SSC.[7] Although previous studies have suggested that PEs are not suitable for young people, recent studies argue that they are a safe and effective method to improve physical abilities such as vertical jump performance,[8] rebound jump height,[9] rate of force development[10] and leg stiffness[11] in young athletes.[12]

An established method to quantify SSC performance is the reactive strength index (RSI) that is derived from the height during a drop jump and the time spent on the ground developing the forces required for that jump.[13] The calculation of RSI and leg stiffness during typical PEs such as cyclical rebounding is a reliable method of developing locomotive activities.[14] The RSI has been developed to monitor the stress on the musculo-tendinous complex during PEs[15] and describe the explosiveness of this action, defined as a subject's ability to be change quickly from an eccentric to concentric contraction.[16] Leg stiffness has previously been positively related with maximal running velocity[17] and stride cadence[18] and can be calculated by dividing the ground reaction force (GRF) by the leg range of motion (ROM).[19] . Furthermore, previous findings support the linear relationship between leg stiffness and peak power during vertical jump. Specifically, Korff et al.[20] found that adolescent participants, aged 16 -18 years, produce greater peak power than pre-adolescent participants aged 11-13 years, and that adolescent participants who demonstrated greater leg stiffness produced greater peak power, whereas in pre-adolescent participants, lower-limb stiffness and peak power were unrelated.

Rhythmic Gymnastics (RG) and Taekwondo (TKD) are sports with different requirements; TKD is a sport in which almost all movements are characterized by their explosiveness. Whilst some movements in RG are characterized by the ability of the gymnast to produce power in a short period of time (e.g. jeté jump), the majority the movements require slower joint movements with greater focus on control and flexibility of the joints. Whilst the specific demands of each sport differ, the ability to move from an eccentric to a concentric contraction is a common feature of both. To the best of our knowledge, only the study by Lloyd et al.[11] has examined the effect of plyometric training on reactive strength index and leg stiffness in male youth athletes. Therefore, the aim of the present study was to investigate the effects of a 4 week plyometric training program on RSI and leg stiffness in female athletes of RG and TKD.

## Methods

A between group, repeated-measures design was used to examine the effect of a plyometric training program on measures of RSI and leg stiffness in young female athletes of TKD and RG. The athletes were randomly assigned to either an experimental (PT) or control (CG) group. All participants completed their regular physical education lessons but PT additionally added a plyometric training program twice weekly for 4 weeks. Participants from both groups were tested on a contact mat for contact time, flight time, jump height, RSI, and leg stiffness one day before the inception and one day after the end of the intervention program.

## Participants

A total of forty-eight athletes, 25 of the TKD and 23 gymnasts of the RG volunteered to participate in this study. No significant differences were found in the aforementioned performance variables between the two sports. Furthermore, no significant differences were found in participant characteristics between PT and CG (Table 1).

Table 1 about here

All participants' parents gave written informed consent before participating in any of the testing. The participants were informed extensively about the experiment procedures and the possible risks or benefits of the project, and they had no musculoskeletal injuries in the previous 3 months. The study was approved by the local institutional Review Board, and all procedures were in accordance with the ethics of University of Athens.

**Experimental procedure**

For each PE session, participants performed a 5 min standardized warm-up that include running at low intensity and light callisthenic exercises. Every training session was supervised by the researchers. The participants were asked to wear the same clothing and footwear during each testing day, and to avoid drinking and eating 1 hour before testing. For the examination of RSI, participants performed four trials of five maximal CMJs with the mean of the best two trials subsequently used for further analysis. After 3 min of rest, a single submaximal hopping test trial (20 hops) was performed in order to examine leg stiffness. Hopping trials were performed in time with a 2.5 Hz quartz metronome (SQ-44, Seiko, Berkshire, United Kingdom) and the mean of the ten consecutive hops closest to the designated metronome (120 bpm) was used for further analysis. All trials were performed on a contact mat (1000 Hz sampling rate, Chronojump, Barcelona, Spain). During RSI trials, the participants were informed to maximize jump height and minimize ground contact time.[21] The first jump in each trial was discounted, with the remaining 4 hops averaged for the RSI analysis[22] which was calculated from the equation of Flanagan and Comyns.[5] Absolute leg stiffness was measured during the submaximal bilateral hopping test. Leg stiffness was calculated according to the following equation, which is known to be a valid and reliable method for youth populations[22]:

$$\text{KN} = \frac{M \times \pi(T_f + T_c)}{{T_c}^2 \left(\frac{T_f + T_c}{\pi} - \frac{T_c}{4}\right)}$$

Where: $K_N$ refers to leg stiffness, M is the total body mass, Tc is equal to ground contact time, and $T_f$ represents the flight time. Relative leg stiffness is the dimensionless leg stiffness relative to body weight and resting leg length.

**Training**

The PT group followed a twice-weekly plyometric training program for 4 weeks similar to that described by Lloyd et al.[11] The duration of plyometric exercises in each session was approximately 3 min for PT, dependent by the planned intensity of the session. A minimum of two days of rest was provided between each training session.[9] The intensity of the program was increased in accordance with previous plyometric training guidelines.[23] Training volume was defined by the number of foot contacts made during each session, starting with 72 contacts in the first session, increasing to 122 contacts in the final 2 sessions. A contact was identified each time the lower extremities perform one attempt of each exercise (see Table 2). Plyometric drills lasted approximately 5–10 s, and at least 90 s rest was allowed after each set.[9] The following exercises were included in the intervention program training (Table 2).

Table 2 about here

## Statistical analysis

Statistical analyses were performed using SPSS version 24 (IBM, New York, USA). A two-way (group x time) ANOVA with repeated measures on the second factor was used for the statistical analysis. Sphericity was checked using Mauchly's test, and the Greenhouse-Geisser's correction on degrees of freedom was applied when necessary. Levene's test of equality of error variances was used to check the assumption of homogeneity of variances. In cases where interaction between time and group was detected, the simple effects were investigated, and Bonferonni's correction was used. In the absence of interaction, the main effects of the two factors (time and group) on the dependent variables were investigated. All statistical significances were tested at $\alpha = 0.05$.

# Results

## Reactive Strength Index

Mean (± SD) and mean difference for RSI during maximal hopping are presented in Table 3. A significant interaction effect was found for RSI ($F(1) = 16.065$, $p < 0.001$, $\eta^2 = 0.259$, power = 0.975). The post hoc analysis showed that RSI significantly increased in the PT for RG athletes by 35% ($p = 0.017$), whereas a significantly reduction by 28% ($p = 0.004$) was revealed in PT for TKD athletes.

Table 3 about here

**Leg Stiffness**

Mean (± SD) and mean difference for contact time and relative leg stiffness during submaximal hopping are presented in Table 4. The statistical analyses revealed that the interaction effect between time and group was statistically significant only for relative leg stiffness ($F(1) = 4.822$, $p < 0.05$, $\eta^2 = 0.095$, $p = 0.575$). The post hoc analysis showed that relative leg stiffness significantly increased in PT for TKD athletes by 31% ($p = 0.008$), whereas remain unchanged ($p > 0.05$) in RG athletes.

Table 4 about here

**Discussion**

The aim of the present study was to investigate the effects of a 4-week plyometric training program on RSI and leg stiffness in female athletes of RG and TKD. Although previous studies have supported the effectiveness of PEs on vertical jump ability,[24, 25] to the best of our knowledge the effects of PEs on RSI has only been examined by Lloyd and colleagues[11] in male youth participants. The primary finding of this study was that 4-week plyometric training produced a significant improvement in RSI in female RG athletes. This finding is in line with the study of Lloyd et al.[11] who found that a 4-week plyometric training program significantly improved RSI performance in 12-year-old boys. In contract, our findings opposed the results of Maylan and Malatesta[9] who investigated 13-year-old boys and found no significantly improvement in RSI after an 8-week plyometric training program.

The improvement of the RSI on RG athletes presented in this study may be attributed to the increased tolerance of these athletes to the eccentric loading of the musculotendinous unit during maximal hopping. The neural mechanistic adaptations that enabled these participants to better tolerate and overcome impact forces experienced in the maximal hopping exercises may be related with increased desensitization of Golgi tendon organs,[26] rate of force development,[10] and greater stretch-reflex contribution.[27] Conversely, the lack of improvement in TKD athletes may be attributed to the fact that the applied plyometric protocol was of moderate intensity and consequently not capable of causing changes in the particular athletes whose training is characterized by intense and rapid implementation of the technical movements required by the sport. On the contrary, the majority of technical skills in the RG are characterized by slow movements and flexibility exercises, and therefore the specific program was enough to cause changes in RSI. Additionally, another factor that related with the improvement of RSI is the increased motor unit recruitment which is affected by the PEs. This explanation has been suggested by previous work of Ramsay and colleagues[28] finding that prepubescent boys were able to activate approximately 10% more motor units after 10 weeks of strength training.

Although a number of studies refer to the benefits of plyometric training on vertical jump performance,[9,12,29] only one study investigated the effects of plyometric training on leg stiffness[11]. The results of this study revealed a significant improvement on leg stiffness on TKD athletes, this agrees with Lloyd et al.[11] who reported a beneficial effect of a 4-week plyometric training program in both 12- and 15-year-old boys. The reduction in ground contact time seems to have increased the leg stiffness; therefore, the applied plyometric training was successful in improving the rebounding properties of the musculotendon unit. Further, as McMahon and Cheng stated according to the spring-mass model the reduction in ground contact time would require more effective use of elastic energy reutilization to maintain center of mass displacement.[19] Furthermore, as Oliver and colleagues stated, the reduction in ground contact time was accompanied by an increase in stretch-reflex activity reliance.[30] It is speculated that this neural adjustment of the extensor muscles of lower limbs that is a strong predictor of leg stiffness in boys,[30] may apply in female TKD athletes. In addition, our results extend previous findings of Lloyd, showing improvement in leg stiffness in 9-year-old female RG athletes.

## Conclusions

The results of the present study showed that the effect of a 4-week plyometric training on RSI and leg stiffness is sport dependent. More specifically, a significant improvement was found for RSI in RG athletes and a significant improvement on leg stiffness on TKD athletes. Further, the applied plyometric program was effective to bring about a reduction on ground contact time and therefore improvement on leg stiffness.

The effectiveness of a 4-week plyometric training that has been documented in adults and in youth boys verified in the present study on young female athletes of different sports; such as rhythmic gymnastics and Tae Kwo Do. This finding is important to practitioners and educators because it allows within a short time to improve the parameters associated with SSC function.

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Table 1: Somatometric characteristics of all participants

| | Taekwondo | | Rhythmic gymnastics | |
|---|---|---|---|---|
| | PT (n = 12) | CG (n = 13) | PT (n = 12) | CG (n = 11) |
| Age (years) | 13.91 ± 3.02 | 12.80± 2.89 | 8.44 ± 2.06 | 9.40 ± 2.87 |
| Body mass (kg) | 48.91 ± 13.26 | 49.50 ± 16.73 | 28.44 ± 6.26 | 30.90 ± 8.96 |
| Body height (cm) | 159.58±14.76 | 158.40 ± 6.55 | 137.89 ± 9.64 | 139.70 ± 14.11 |
| Training (years) | 5.83 ± 3.63 | 6.00 ± 2.98 | 3.78 ± 1.64 | 4.70 ± 2.91 |

PT: plyometric training group, CG: control group

**Table 2:** Plyometric training program outline. For the calculation of foot contact during in each session the sum of all contacts was calculated.

| | Week 1 | | Week 2 | | Week 3 | | Week 4 | |
|---|---|---|---|---|---|---|---|---|
| **Exercise** | **Session 1** | **Session 2** | **Session 3** | **Session 4** | **Session 5** | **Session 6** | **Session 7** | **Session 8** |
| Double tuck jumps | 2 × 6 | | | 2 × 10 | 2 × 8 | 2 × 10 | | 4 × 5 |
| Squat jump | 2 × 6 | | 2 × 6 | | | | | |
| Poggo hopping | | 2 × 6 | 3 × 6 | | 4 × 5 | 2 × 10 | 4 × 8 | 4 × 10 |
| Lateral hops | 2 × 8 | 2 × 8 | 3 × 6 | 3 × 8 | | | | |
| Ankle jumps | | 2 × 8 | | | 3 × 8 | | 3 × 8 | 3 × 10 |
| Power skipping | | 2 × 10 | | 3 × 8 | 3 × 8 | | 3 × 8 | |
| Standing long jump | | 3 × 4 | 4 × 4 | | | | 4 × 4 | |
| Single leg jump | | | | 2 × 6 | | 3 × 6 | | 2 × 8 |
| Hurdle hops | | | 2 × 6 | 2 × 8 | | 2 × 10 | | 2 × 8 |
| Single Leg Bench Jumps | 2 × 8 | | | | | | 2 × 10 | |
| Jumping lunge alternative | 2 × 8 | | | | | | | |
| Jumping lunge alternative backward | | | 2 × 6 | | 2 × 8 | 2 × 8 | | |
| **Total foot contacts** | **72** | **76** | **88** | **96** | **100** | **114** | **116** | **122** |

Table 3: Mean (± SD) values for Reactive Strength Index (RSI) during maximal hopping

| | Reactive Strength Index (mm·ms$^{-1}$) | | |
|---|---|---|---|
| Group | Pre | Post | MD (95%CI) |
| RG | | | |
| PT | 0.330 ± 0.06 | 0.444 ± 0.13* | 0.044 0.184 |
| CG | 0.339 ± 0.11 | 0.364 ± 0.10 | -0.072 0.122 |
| TKD | | | |
| PT | 0.618 ± 0.27 | 0.484 ± 0.12 | -0.302 0.033 |
| CG | 0.614 ± 0.20 | 0.433 ± 0.10 | -0.401 0.040 |

*: significant different from pre training. MD: mean difference, RG: rhythmic gymnastics, TKD: taekwondo, PT: plyometric training group, CG: control group.

Table 4: Mean (± SD) values for contact time and relative leg stiffness during submaximal hopping.

| | Contact time (ms) | | | Relative leg stiffness | | |
|---|---|---|---|---|---|---|
| Group | Pre | Post | MD (95%CI) | Pre | Post | MD (95%CI) |
| RG | | | | | | |
| PT | 0.490 ± 0.06 | 0.408 ± 0.10 | -0.018 -0.144 | 8.436 ± 1.94 | 9.326 ± 1.67* | 0.092 1.686 |
| CG | 0.528 ± 0.12 | 0.479 ±0.14 | -0.191 0.092 | 8.735 ± 1.97 | 8.428 ± 2.51 | -2.007 1.393 |
| TKD | | | | | | |
| PT | 0.369 ± 0.13 | 0.350 ± 0.14 | -0.070 0.031 | 13.966 ± 4.81 | 18.243 ± 5.29* | 0.752 7.802 |
| CG | 0.310 ± 0.13 | 0.302 ± 0.11 | -0.041 0.024 | 15.348 ± 5.03 | 15.660 ± 5.15 | -0.265 0.888 |

*: significant different from pre training. MD: mean difference, RG: rhythmic gymnastics, TKD: taekwondo, PT: plyometric training group, CG: control group.