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Jump-Rope Training: Improved 3-km Time-Trial Performance in Endurance Runners via Enhanced Lower-Limb Reactivity and Foot-Arch Stiffness

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Context: Plyometric training promotes a highly effective neuromuscular stimulus to improve running performance. Jumping rope (JR) involves mainly foot muscles and joints, due to the quick rebounds, and it might be considered a type of plyometric training for improving power and stiffness, some of the key factors for endurance-running performance. ***Purpose:*** To determine the effectiveness of JR during the warm-up routine of amateur endurance runners on jumping performance, reactivity, arch stiffness, and 3-km time-trial performance. ***Methods:*** Athletes were randomly assigned to an experimental (n = 51) or control (n = 45) group. Those from the control group were asked to maintain their training routines, while athletes from the experimental group had to modify their warm-up routines, including JR (2–4 sessions/wk, with a total time of 10–20 min/wk) for 10 weeks. Physical tests were performed before (pretest) and after (posttest) the intervention period and included jumping performance (countermovement-jump, squat-jump, and drop-jump tests), foot-arch stiffness, and 3-km time-trial performance. Reactive strength index (RSI) was calculated from a 30-cm drop jump. ***Results:*** The 2 × 2 analysis of variance showed significant pre–post differences in all dependent variables ($P < .001$) for the experimental group. No significant changes were reported in the control group (all $P \geq .05$). Pearson correlation analysis revealed a significant relationship between Δ3-km time trial and ΔRSI ($r = -.481$; $P < .001$) and ΔStiffness ($r = -.336$; $P < .01$). The linear-regression analysis showed that Δ3-km time trial was associated with ΔRSI and ΔStiffness ($R^2 = .394$; $P < .001$). ***Conclusions:*** Compared with a control warm-up routine prior to endurance-running training, 10 weeks (2–4 times/wk) of JR training, in place of 5 minutes of regular warm-up activities, was effective in improving 3-km time-trial performance, jumping ability, RSI, and arch stiffness in amateur endurance runners. Improvements in RSI and arch stiffness were associated with improvements in 3-km time-trial performance.

Keywords: rope jumping, running, plyometric exercises, resistance training, stretch reflex

The importance of resistance training (RT) for endurance runners has been extensively demonstrated in the last decade.[1] This has 2 main goals: maximizing athletic performance (eg, running economy [RE] or velocity at VO_2max [vVO_2max]) and minimizing the risk of injury.[2] Specifically, RT focused on neural adaptations has been shown as one of the most efficient strategies for improving sport performance in athletes.[3] The benefits of RT include improvements also in RE (from 3.0% to 8.1%) through different mechanisms, such as changes in mechanical efficiency, muscle coordination, or motor recruitment patterns.[1,4] Finally, these adaptations affect positively to athletic performance, with some previous studies[4–6] reporting improvements in 3- to 5-km runs after a protocolized RT program. However, endurance runners still doubt about the advantages of RT[4] and still think "more is better" by accumulating greater running volumes per week.[7] Some reasons for not including RT in their trainings might be the fear of interference effects, the lack of knowledge, time, equipment and facilities, or enjoyment.[4]

One of the most frequently studied types of RT in endurance runners is plyometric training (PT), with or without external loads.[4] This type of training promotes a highly effective neuromuscular stimulus. Whereas a traditional heavy RT program induces neural and hypertrophic adaptations, leading to a dilution of the mitochondrial volume density, PT may lead preferentially to adaptations like increased rate of activation of motor units[8,9] with the advantage of requiring reduced physical space, time, and equipment to complete the training sessions.[7] Furthermore, it produces improvements in running performance and RE.[4] For instance, Berryman et al[3] compared PT with dynamic weight training in runners, showing that the former induced a higher efficiency in the energy cost of running. This can be explained because of improvements in motor unit recruitment and synchronization after PT.[4] However, these PT protocols have shown some limitations such as not related with running technique (box jumps), an elevated volume (ie, 2000 jumps in 6 wk), low number of participants, poor description of PT protocols, among others.[10] That is, PT can be a good type of training for endurance runners compared with other traditional RT, but coaches should be cautious about the aforementioned considerations.

Jumping rope (JR) is a consecutive jump exercise with turning the rope, involving mainly foot muscles and joints, due to the quick rebounds.[11] Therefore, JR might be considered a type of PT for improving power and stiffness, some of the key factors for

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endurance running performance.[4] Furthermore, the rope enables to combine PT with running technique (eg, skipping, dynamic rope jumping, unilateral jumps),[12] reducing the time to achieve both goals, with a high level of adherence and enjoyment[13] that can be used during warm-ups. Therefore, it seems that, compared with other types of PT as box or hurdle jumps, JR can improve the athletic performance on endurance runners with low-cost investments and time efficiency.

However, there are few research reports that focus on the effects of including JR in the warm-up routines of training sessions.[7,11] For instance, besides the positive effects of PT on endurance runners,[1,4,14] more than 70% of amateur endurance runners included only continuous run during warm-ups, using low-intensity running as the most common strategy.[7] Related to this, running exposure has been strongly correlated with overuse injuries in endurance runners.[15] Taking this context into account, low-time cost strategies to improve stiffness and performance have the potential to be included during warm-ups.

To the authors' knowledge, there are no studies focused on analyzing the effects of a PT warm-up protocol on amateur endurance runners. Furthermore, no previous studies exist about including low-cost strategies to improve athletic performance in endurance runners. For these reasons, the aim of this study is to determine the effectiveness of incorporating JR during the warm-up routine of amateur endurance runners on jumping performance, reactivity, arch stiffness, and 3-km time-trial performance.

Methods

Subjects

A total of 96 amateur endurance runners (51 males and 45 females; age range: 18–40 y) successfully completed the study (Table 1). Participants met the following inclusion criteria: (1) should be 18 years and older; (2) able to run 10 km in less than 50 minutes; (3) recreationally trained (3–5 running sessions per week); (4) not to be involved in any RT program, including PT; and (5) have not suffered from any injury within the last 6 months before data collection. Initially, 105 participants who fulfilled the inclusion criteria were selected to participate in this study. To be included in the final analyses, each participant needed to complete the training program and attend pre–post assessments. Related to these strict requirements, 9 participants were excluded from data analysis (N = 96; Figure 1). Participants were randomly assigned to the experimental group (EG; n = 51, women = 24) or the control group (CG; n = 45, women = 21). A research assistant who was not involved in the data collection, using random numbers generated in Microsoft Excel 2016, conducted randomization independently. After receiving detailed information on the objectives and procedures of the study, each participant signed an informed consent form, which complied with the ethical standards of the latest version of the World Medical Association's Declaration of Helsinki (2013); it was made clear that the participants were free to leave the study if they were unfit. The University of Jaén's Ethics Committee approved the study.

Table 1 Descriptive Characteristics of the Participants

Variable	EG (n = 51)	CG (n = 45)	P^a
Age, y	27.2 (8.6)	26.1 (6.3)	.467
Height, m	1.72 (0.1)	1.71 (0.1)	.790
Body mass, kg	66.0 (10.4)	65.7 (9.1)	.852
BMI, kg/m^2	22.3 (2.0)	21.9 (2.2)	.472

Abbreviations: BMI, body mass index; CG, control group; EG, experimental group. Note: Data are presented as mean (SD).
[a] Chi-square test was conducted.

Design

The study was conducted between January and April 2019. Using a between-group design (EG and CG), 96 athletes were assessed. Testing was completed at week 0 (pre) and at week 11 (post) to monitor changes over the course of a 10-week training program. Thus, physical tests were performed before (pretest) and after (posttest) the 10-week intervention period.

Athletes from the CG were asked to maintain their training routines, whereas athletes from the EG modified their warm-up routines, but maintained their running routines (see Table 2 for more information about training background of both EG and CG).

Training

Athletes from the EG included JR during their warm-up routines (ie, just after the running-based exercises in the warm-up, 2–4 sessions per week, with a total time of 10–20 min/wk) for 10 weeks. Since athletes replaced 5 minutes of their habitual warm-up routines with JR drills, 2 to 4 times per week, the current JR training was easily incorporated into the regular training schedules of the participants. Before starting the training program (week 0), the EG participants were instructed with technical key points about JR. These included (1) rope rotation should be generated by the wrists with minimal movement of the elbows and shoulders, (2) jump height should be maximized and ground contact time should be minimized, and (3) landing should be softened on the forefoot and with the knees slightly flexed. More details about the 10-week JR training program can be checked in Table 3. The participants from the CG maintained their training plans, whereas the athletes from EG just changed the content of the warm-up routines, with no other changes in their training program.

Methodology

The athletes were instructed to refrain from intense exercise (ie, score of ≥15 in the rating of perceived exertion scale of 6–20) 2 days preceding testing (weeks 0 and 11, pretest and posttest, respectively). Testing sessions were conducted 3 to 4 days before starting the intervention and 3 to 4 days after finishing it (pretest and posttest, respectively). They were not allowed to eat during the hour preceding the test or to consume coffee or other products containing caffeine during the preceding 3 hours. Pretesting and posttesting were conducted at the same time of the day to avoid the influence of the circadian rhythm and under similar environmental conditions (20°C–24°C).

Either at pretest or posttest, athletes were tested individually, and participation involved the execution of 3-km time trial on an outdoor 400-m synthetic track. The elapsed time (in seconds) for the 3-km running was registered for the subsequent analysis. The only instruction given to participants was to finish the race as fast as they could.

Before starting the running trial, body height (in centimeters) and body mass (in kilograms) were determined using a precision stadiometer and mechanical scale (Seca 222 and 634, respectively; Seca Corp, Hamburg, Germany). All measurements were taken with the participants wearing underwear. Also, the arch height and the arch stiffness of the right foot were assessed. Arch height

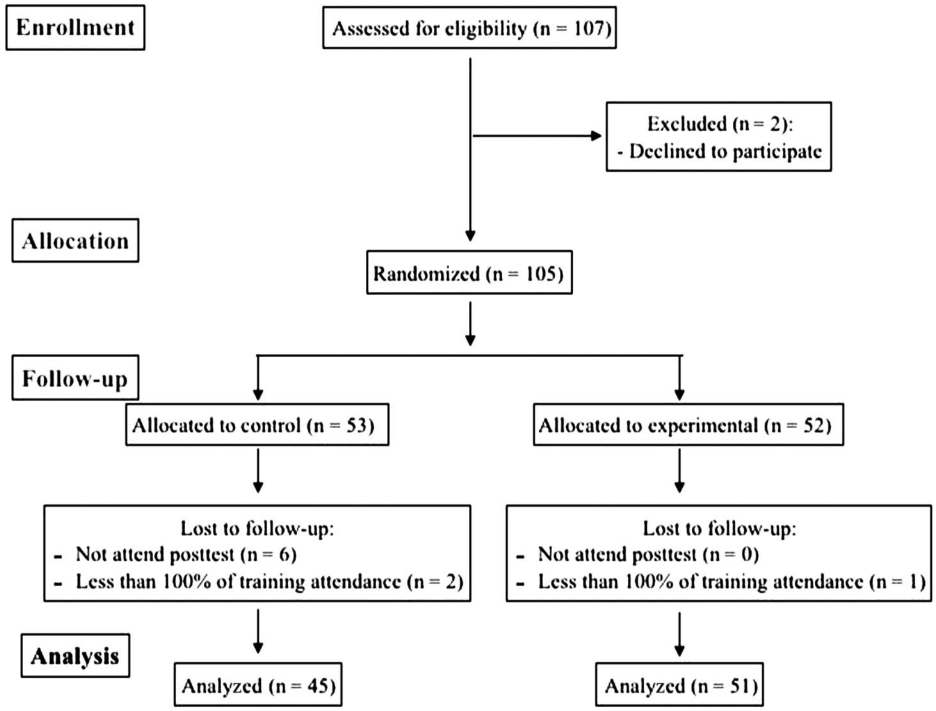

Figure 1 — CONSORT diagram of the full recruitment and randomization process.

Table 2 Characteristics of the Training Plans of the Participants During 2 Periods[a]

Variable	EG (n = 51)	CG (n = 45)	*P*
10 wk before intervention			
Number of running sessions per week	4.0 (0.7)	4.1 (0.4)	.772
Running volume,[b] km/wk	41.3 (5.1)	42.4 (6.9)	.373
Running volume,[b] h/wk	4.6 (1.3)	4.7 (1.3)	.801
10 wk of intervention			
Number of running sessions per week	4.2 (0.6)	4.4 (0.5)	.690
Running volume,[b] km/wk	42.1 (6.5)	40.5 (5.6)	.493
Running volume,[b] h/wk	4.8 (1.1)	4.5 (1.2)	.352

Abbreviations: CG, control group; EG, experimental group.
[a] Two periods: (1) 10 weeks before starting the intervention and (2) 10 weeks of intervention. [b] Warm-up and cooldown routines are included.

Table 3 Jump-Rope Training Program

Weeks	Sessions per week	Time per session, min	Work:rest ratio, s	Cadence, rpm	Type	Total weekly time, min
1–2	2	5	30:30	100–120	Bilateral	10
3–4	3	5	30:30	100–120	Bilateral	15
5–6	3	5	30:30	120–140	Unilateral—alternating	15
7–8	4	5	30:30	120–140	Unilateral—alternating	20
9–10	4	5	40:20	120–14	Unilateral—alternating	20

was defined as the height of the dorsum of the foot normalized to truncated foot length. Truncated foot length was defined as the length of the foot from the heel cup (most posterior portion of the calcaneus) to the center of the medial joint space of the first metatarsal phalangeal joint.[16] Arch stiffness, a measure of the amount of deformation per unit of load, was defined as the change in arch height index (AHI) due to the increase in load between sitting and standing conditions. Measurements were taken by a single investigator using the AHI Measurement System.[16] Butler et al[16] reported high intrarater and interrater reliability. Participants were asked to sit in a height-adjustable chair. Then, the chair was adjusted to keep knees and hips under a 90° alignment and with slight contact between plantar foot surface and the measurement platform. A specially designed platform for undertaking this measurement was used.[17] The dorsum of the foot at 50% of total foot length was measured with a digital caliper. The total foot length was considered from the most posterior aspect of the calcaneus fixed at a heel cup to the most distal aspect of the longest toe. It was repeated in a bipedal stance position assuming body weight. Both feet were fixed in the heel cups positioned 15 cm apart. The dorsal arch height difference was calculated as the difference between dorsal arch in bipedal standing and in sitting position, known as sit-to-stand difference, whereas the AHI was calculated as follows[18]:

$$\text{AHI} = \text{Dorsum height}/\text{Truncated foot length} \tag{1}$$

Based on a previous study,[19] the arch stiffness was calculated by assuming a 40% change in load between seating and standing conditions (that value of change reflected the difference between half the body weight and the weight of the foot + shank) as follows:

$$\text{Arch stiffness} = (0.40 \times \text{Body mass})/(\text{AHI [seated]} - \text{AHI [standing]}) \tag{2}$$

The average of 3 repeated measurements was computed and used for subsequent analysis. The static foot posture and foot mobility measures have reported moderate to good intrarater reliability (intraclass correlation coefficient = .81–.99) and moderate to good interrater reliability (intraclass correlation coefficient = .58–.99), respectively.[17,18]

After anthropometric and foot measurements, at both pretest and posttest, the participants performed a standardized warm-up (ie, mobility, continuous low-intensity running, jumping, and sprinting bouts) and a battery of jumping tests (squat jump [SJ], countermovement jump [CMJ], and 30-cm drop jumps [DJ30]). The participants were unexperienced athletes in terms of plyometric drills and jumping test. To make sure the execution was correct, 2 familiarization sessions were carried out during the previous week before testing. The SJ, CMJ, and DJ30 tests were recorded using the OptoGait system (Microgate, Bolzano, Italy), which has been previously used in a similar study.[20] This device measures the contact time on the floor and the flight time using photoelectric cells. Flight time was used to calculate the height of the rise using the body's center of gravity. Athletes performed 2 trials of every test, with a 15-second recovery period between them, with the best trial being used for the statistical analysis. As described by a previous study,[21] during SJ, participants were instructed to adopt a flexed knee position (approximately 90°) during 3 seconds before jumping, whereas during CMJ, no restriction was imposed over the knee angle achieved before jumping. Jumping tests were executed with arms akimbo. Takeoff and landing were standardized to full knee and ankle extension on the same spot. The participants were instructed to maximize jump height. For the DJ30, participants were instructed to maximize jump height and minimize ground contact time after dropping down from a 30-cm drop box.[22] Reactive strength index (RSI) was calculated as follows:

$$\text{RSI} = \text{Flight time (ms)}/\text{Contact time (ms)} \tag{3}$$

Statistical Analysis

Data are presented as group mean values (SDs). After data normality assumption was verified with the Levene test, analyses of variance were used to detect differences between study groups in all variables at pretest and posttest. Measures of dependent variables were analyzed in separate 2 (groups) × 2 (time [pre, post]) analyses of variance with repeated measures on time, with Bonferroni-adjusted α. The magnitude of the differences between values was also interpreted using the Cohen *d* effect size (ES) (between-group differences). ESs are reported as follows: trivial (<0.2), small (0.2–0.49), medium (0.5–0.79), and large (≥0.8). A Pearson correlation analysis was conducted between changes (Δ; eg, 3-km time trial at pretest minus 3-km time trial at posttest) experienced in athletic performance, RSI, and stiffness. Finally, a simple linear regression analysis was used to determine the association between the improvement in the 3-km test (dependent variable: Δ3-km time trial) and the improvements in RSI and arch stiffness (independent variables: ΔRSI and ΔStiffness) during the intervention. Data analysis was performed using the SPSS software (version 21; SPSS Inc, Chicago, IL). Significance levels were set at $\alpha = 5\%$.

Results

No significant between-group differences ($P \geq .05$) were found in age, anthropometric characteristics, and sex distribution at baseline (before training intervention; Table 1). Table 2 presents the characteristics of training plans of athletes from both CG and EG before starting the 10-week intervention period and during that period, and no significant between-group differences were found (all Ps ≥ .05).

The effects of the intervention on dependent variables are displayed in Table 4. The main group × time effect revealed significant differences in all variables ($P < .001$). The post hoc analysis showed significant differences in all variables (all Ps < .001, small ES [arch stiffness, SJ, and 3-km time trial] and moderate ES [CMJ, DJ30 cm, and RSI]) for the EG, whereas no significant changes were reported in the CG (all Ps ≥ .05, trivial ES).

A Pearson correlation analysis revealed significant relationship between Δ3-km time trial and ΔRSI ($r = -.481$; $P < .001$) and ΔStiffness ($r = -.336$; $P < .01$). The linear regression analysis showed that Δ3-km time trial was associated with ΔRSI and ΔStiffness ($R^2 = .394$; $P < .001$).

Discussion

The aim of this study was to determine the effectiveness of a 10-week JR training program, incorporated into the warm-up routines of amateur endurance runners, on jumping performance, reactivity, arch stiffness, and 3-km time-trial performance. The main findings indicate that JR training was effective for the improvement of jumping performance, reactivity, arch stiffness, and 3-km time-trial performance. Although previous studies incorporated JR training as a strategy to improve the physical fitness of athletes,[11,23] to our knowledge, this is the first study to analyze the effects of a JR training approach in endurance runners. Moreover, the current JR training approach incorporated an ecological-valid (practical) approach. In this sense, athletes replaced 5 minutes of their habitual warm-up routines with JR drills. In addition, the replacement was applied only 2 to 4 times per week. Therefore, the current JR training approach was easily incorporated into the regular training schedules of the participants.

Table 4 Effects of a 10-Week Jump-Rope Training Program on Arch Stiffness, Jumping, and 3-km Time-Trial Performance of Amateur Endurance Runners

Variable	Groups	Pretest, mean (SD)	Posttest, mean (SD)	Post – pre (Δ, %)	*P* (group × time)	Bonferroni post hoc *P* (Cohen *d*)
Arch stiffness (body mass/AHI units)	EG (n = 49)	925.5 (388.7)	997.95 (373.17)	72.4 (7.8)	<.001	<.001 (0.23)
	CG (n = 45)	947.7 (418.8)	949.01 (427.31)	1.33 (0.1)		.944 (0.01)
CMJ, cm	EG (n = 47)	28.59 (5.79)	31.59 (6.01)	3.0 (10.5)	<.001	<.001 (0.52)
	CG (n = 44)	29.46 (7.15)	29.30 (7.07)	−0.2 (0.5)		.165 (0.01)
Squat jump, cm	EG (n = 47)	23.72 (3.90)	25.08 (3.76)	1.4 (5.7)	<.001	<.001 (0.41)
	CG (n = 44)	24.75 (5.70)	24.66 (4.35)	−0.1 (0.4)		.525 (0.02)
DJ30, cm	EG (n = 47)	25.40 (3.47)	26.84 (3.18)	1.4 (5.7)	<.001	<.001 (0.54)
	CG (n = 44)	26.65 (4.96)	26.76 (4.58)	0.1 (0.4)		.193 (0.02)
RSI, ms/ms	EG (n = 47)	1.92 (0.45)	2.17 (0.42)	0.3 (13.0)	<.001	<.001 (0.62)
	CG (n = 44)	1.91 (0.41)	1.92 (0.41)	0.01 (0.5)		.280 (0.03)
3-km time trial, s	EG (n = 44)	774.6 (79.5)	751.7 (65.8)	−22.9 (3.0)	<.001	<.001 (0.44)
	CG (n = 42)	762.1 (87.5)	750.8 (83.6)	−11.3 (1.5)		.136 (0.12)

Abbreviations: AHI, arch height index; CMJ, countermovement jump; DJ30, 30-cm drop jumps; RSI, reactive strength index.

One of the main findings from the current intervention was the significantly greater improvement of 3-km time-trial performance in the JR training group (3%, ES = 0.4) compared with the CG (1.5%, ES = 0.1). Such improvement has been previously reported in endurance runners, from different fitness levels, after PT interventions[1] and may be related to adaptations in several physiological and biomechanical determinants of endurance running performance,[24] with the most relevant being probably RE.[1] In fact, improvements in RE have been associated with increased RSI and stiffness,[1,14] which is in line with the results obtained in the current study (ie, Δ3-km time trial was significantly associated with ΔRSI and ΔStiffness). Although improvements in neuromuscular factors presumably mediated the improvement in the 3-km time-trial performance, the high jumping frequency involved in the current JR training intervention may have also induced an important cardioventilatory stimulation (eg, 90% of VO_2max),[25] with a potential positive impact on vVO_2max.[26] Future studies may elucidate if high-frequency JR training, such as the one applied in this intervention, may contribute to improvements in cardioventilatory parameters (eg, VO_2max, VO_2peak, or vVO_2max).

The relationship between jumping performance and running endurance performance has been previously established.[27] In this regard, an important finding in the current study was the greater increase of explosive strength performance requiring slow stretch-shortening cycle (SSC) action (ie, CMJ) and fast SSC action (ie, DJ30) in the JR training group compared with the CG. Improved reactivity (ie, DJ30) may be related to increased neural drive to the agonist muscles, improved intermuscular coordination, changes in muscle size and/or architecture, changes in single-fiber mechanics, among others.[5] Such improvements may reduce the time the athlete's foot spends in contact with the ground during running,[5] favorably affecting performance during running endurance events.

Another finding from this study was the significantly greater improvement of arch stiffness in the JR training group (7.8%) compared with the CG (0.1%). Such improvement is similar to the one previously reported for endurance runners after PT.[6] Improvements in stiffness at the muscle fiber level may occur mainly on fast-twitch fibers.[28] It may be possible that endurance runners, who usually have a relatively more developed slow-twitch fiber phenotype,[24] had greater ceiling for improvements in their fast-twitch fibers.[29] Although improvements in stiffness have been observed in previous PT studies, including endurance runners,[6] others have found mixed findings[28] or not such an improvement.[28,30] Part of the disagreement among studies might be related with the assessment technique and the structures assessed. Whereas the current work evaluated arch stiffness, defined as the change in AHI due to the increase in load between sitting and standing conditions, Spurrs et al[6] obtained musculotendinous stiffness of the lower limb through the oscillation technique by performing an isometric contraction on an instrumented seated calf raise machine. Likewise, Fouré et al[28] focused on passive stiffness of the gastrocnemii defined as the slope of the length–tension relationship for the common range of gastrocnemii length. In this regard, current results suggest that the assessment of arch stiffness may be a sensitive measurement technique for stiffness changes in endurance runners.

It seems logical that those improvements in jumping ability and arch stiffness are linked to improvements in reactivity (ie, RSI in the current work). Previous studies have revealed a strong association between those parameters and running performance.[31,32] Current results demonstrated that the JR training group improved the RSI (13%) when compared with the CG. This index denotes that per each unit of time the foot is on the ground, greater jump height (flight time) is achieved, an indirect marker of greater rate of force development. Additionally, the linear regression analysis showed that Δ3-km time trial was associated with ΔRSI and ΔStiffness (R^2 = .394; $P < .001$), which reinforces the association between lower body stiffness and reactivity with athletic performance in endurance runners.

Of note, the improvements in jumping performance in the JR training group were achieved after an intervention with a focus on jump repetitions with short contact time. In this context, it is tempting to speculate that the time the athlete's foot spends in contact with the ground during jumps can modulate training-related adaptations in endurance runners. However, this should be tested in future studies comparing interventions with different contact times during the jumps.

Practical Applications

The replacement of 5 minutes of regular warm-up routines, 2 to 4 times per week, with JR training drills might be an effective and safe resource to incorporate into the training schedule of amateur endurance runners as a time-efficient strategy to improve several proxies associated with endurance running performance, such as jumping, RSI, stiffness and, mostly, 3-km time trial. Moreover, JR training drills are probably related to lower mechanical stress than other plyometric exercises like drop jumps performed from high heights. This may help to "preserve" the musculoskeletal system from excessive loading, especially before habitual running sessions.

Conclusions

When compared with a control warm-up routine previous to endurance running, 10 weeks (2–4 times per week) of JR training, in replacement of 5 minutes of regular warm-up activities, was effective in improving 3-km time-trial performance, jumping ability involving concentric (SJ), slow SSC (CMJ), fast SSC (DJ30), RSI, and arch stiffness in amateur endurance runners. Moreover, improvements in RSI and arch stiffness were associated with improvements in 3-km time-trial performance.

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