



Research paper

Combined strength and plyometric exercise training improves running economy and muscle elastic energy storage and re-use in young untrained women



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ABSTRACT

Introduction: Both resistance and stretch-shortening cycle exercise have positive effects on physical abilities and health related factors. In the present experiment we tested the hypothesis that an 8-week-long combined strength and stretch-shortening cycle exercise training is superior to strength training alone in the development of walking and running economy in healthy untrained women.

Methods: Twenty untrained female college students (age = 21.5 ± 2.1 years, body mass index = 22.3 ± 2.9) were divided into two experimental groups. Both groups performed own-body resistance exercises three times per week but one group performed additional stretch-shortening cycle exercises. Countermovement jump force as well as maximal voluntary isometric torque and elastic energy storage and re-use in quadriceps muscle were measured. Running and walking economy was quantified by measuring maximal oxygen consumption during a treadmill test.

Results: Isometric torque improved uniformly in the two groups ($p < 0.05$), however countermovement jump force, elastic energy storage and re-use as well as running economy improved selectively after strength and additional stretch-shortening cycle exercise ($p < 0.05$). Walking economy was unaffected in either of the experimental groups.

Conclusion: This study suggests that improved elastic energy storage and re-use rather than maximum muscle contractility may account for the changes in countermovement jump force and running economy after additional stretch-shortening cycle exercise. The present data should be taken into consideration for understanding the favourable effects of stretch-shortening cycle exercise training in the young untrained population.

1. Introduction

Strength training is an important activity for the untrained population in the improvement of physical fitness and health related factors. In numerous studies it has been demonstrated that the use of resistance (either own body weight or external resistance) during various tasks benefit muscle growth and muscle function [1,2] important factors in the precedence of orthopaedic disorders. In addition, resistance exercises are used for the prevention of ageing-induced muscle wasting

and mobility disability [3]. Various types of resistance exercise modalities are recommended for the untrained population such as eccentric and concentric muscle contractions [4–7] to increase functional abilities, which are related to the improvement of skeletal muscle mechanics. These exercises, however do not always improve the muscles ability to contract rapidly [8,9], which is an important contributor to the prevention of falls and injuries. Recently, stretch-shortening cycle (SSC) exercises (also called plyometrics) have been used to target general weakness and contraction speed in untrained individuals [10].

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Furthermore, a previous study demonstrated that the combination of resistance and SSC exercise training is more effective, compared with resistance exercise alone [11].

The multivariate benefits of SSC exercise have been described in various studies recruiting athletes, recreationally trained, untrained, and even elderly individuals. SSC exercise improves maximal voluntary contraction (MVC) force [12,13], explosive force, power [14,15], and even muscle size [14,16]. The most pronounced improvement, however, is usually detected in vertical jump height [17,18], which is often explained with the improved elastic energy storage and reuse in muscle. It has also been suggested that SSC exercise improves running economy (RE) [19]. RE can be defined as the energy demand for a given velocity of running [20]: individuals with greater RE use less oxygen while running. One of the reasons can be that they store and return more elastic energy in the muscles during the SSC than people with poor RE at the same speed. While previous studies suggested that SSC exercises improve muscle economy through enhanced elastic energy storage, data is limited to athletes' population [21]. In addition, data is unavailable whether SSC improves economy during walking (WE), which also incorporates the natural sequence of SSCs.

We hypothesized that additional SSC exercise bouts would selectively improve elastic energy storage and reuse in young untrained subjects participating in an 8-week-long traditional own-body resistance exercises training program. We further hypothesized that SSC exercise-induced mechanical adaptations accumulate into improvements in WE and RE.

2. Methods

2.1. Subjects and experimental procedure

Twenty untrained female college students volunteered to participate in this study after an announcement (placing adverts on notice boards) on the university campus. Inclusion criteria were, females between 18 and 25 years. Subjects were experienced in various physical activities such as aerobics, jogging, walking, and dance, but did not take part in any individual or organized physical activity during the training intervention. Other exclusion criteria were current injury or previous surgery in lower extremities or spine, contraindications to exercise, movement disorders, any types of diagnosed cardiovascular disease or abnormal blood pressure, and participation in any resistance or cardiovascular exercise program in the past three months (as recommended by the American College of Sports Medicine), to ensure that subjects begin the experiment without previous adaptation or exercise-induced muscle damage. Subjects' descriptive characteristics (including anthropometric and cardiorespiratory data) are presented in Table 1. All the 20 subjects participated in the same 8-week-long own-body strength

Table 1

Descriptive characteristics (including anthropometric and cardiovascular data) of the ST + SSC and the ST group. Note: all data are pre-intervention (baseline) data. BMI = Body mass index, HR = heart rate, RER = respiratory exchange ratio.

Descriptive variables	ST + SSC		ST	
	mean	SD	mean	SD
Age (years)	21.4	2.6	21.6	1.7
Body height (m)	165.6	4.4	166.9	5.8
Body weight (kg)	61.6	6.6	64.6	11.2
BMI (kg/m ²)	22.4	2.4	22.3	3.3
Body fat (%)	23.5	3.9	24.0	5.4
Resting HR (bpm)	70	8	72	7
Peak HR (bpm)	180	16	183	13
Peak VO ₂ (ml/kg/min)	29.6	1.4	29.6	2.0
Peak RER	1.01	0.08	1.04	0.07
Resting O ₂ pulse (ml/beat)	2.8	0.7	2.6	0.4



Fig. 1. Dynamometric testing of the knee extensor muscles using Multicont II device.

exercise training program. Because baseline measurements were taken for all subjects before the beginning of the exercise intervention, therefore subjects were assigned into two groups using the stratified randomization method. VO₂max is considered the main criterion measure in the present study, therefore we used the baseline VO₂max values as covariates for the randomization process to balance baseline group means. One group participated only in the strength training (ST group, n = 10), and the other group performed additional SSC exercises (ST + SSC group, n = 10). Two days before and after the training program, subjects were tested in various performance tests. Before any testing and training, informed signed consent was obtained. The experimental protocol, which respected the Declaration of Helsinki, was approved by the University Ethical Committee (approval number: 5812).

2.2. Quadriceps MVC torque

Multicont II dynamometer (Mediagnost, Budapest and Mechatronic Ltd, Szeged, Hungary, sampling rate: 1000 Hz) was used to test the mechanical properties of the quadriceps femoris (Fig. 1). Subjects were seated on the dynamometer's padded seat and performed unilateral isometric knee extensions at 70° of knee flexion (0° = full extension). Before any testing, three warm-up trials were allowed with 50, 70, and 90% of the perceived maximum effort. This followed three repetitions maximal voluntary isometric contractions with three minutes recovery between trials. The peak torque during contractions was determined and the best value was used for statistics. Maximal voluntary isometric torque was also measured at 30° knee angle to determine the trigger threshold for initiating the SSC test contraction (described below).

2.3. Quadriceps SSC function

To determine SSC function, on the same dynamometer, subjects performed a quadriceps SSC test in which the dynamometer rapidly

applied a preset amount of energy to stretch the quadriceps [22]. The eccentric phase of the contraction started at 30° of knee flexion and the subject had to exert force against the lever arm as fast and forcefully as possible. When the subject reached 60% of isometric MVC torque measured previously at 30° of knee flexion, the dynamometer's lever arm started to rotate in the direction of knee flexion. Subjects were instructed to resist the rotating lever arm maximally, stop it within the shortest range of motion (eccentric phase), and then extend the knee without a time delay and as fast as possible to 30°. The initial velocity of the lever arm was 300°·s⁻¹ and the preset amount of stretch-load was half of the baseline MVC. Based on our previous observations such stretch-load to the quadriceps is optimal to produce a knee flexion similar to that in a vertical jump test [22]. The applied stretch-load represents the amount of work the dynamometer's lever arm performed on the shank to flex the knee joint. As the eccentric knee flexion progresses, the energy stored in the servomotor diminishes to zero (the lever arm stops) and some of the energy is stored in the quadriceps muscle. The instructions given to the subjects ensured that the transfer of energy that stretched the quadriceps muscle occurred in a short time and over a small range of motion so that the concentric contraction would start immediately. During the concentric phase, the dynamometer's motor was automatically turned off and provided resistance through friction and the inertia of the lever arm and lower leg. Torque and knee angle as function of time (Fig. 2) were recorded for each contraction and, similarly to Kyröläinen, et al. [23], we calculated the positive mechanical work (W_{ssc}) during the SSC by integrating the torque-position curve between the boundaries of the range of motion:

$$W(J) = \int_{\theta_1}^{\theta_n} M_{(\theta)} \cdot d\theta$$

where M = torque, $d\theta$ = angular displacement, and θ_1 and θ_n represent the first and the last knee angle data points, respectively. Total time to complete the SSC contraction (T_{ssc}) was also determined.

To examine the ability to store and re-use elastic energy, after the SSC test, a pure concentric contraction was performed. For each subject this contraction started exactly at the knee angle where the dynamometer's lever was stopped during the SSC test (transition phase) and ended in the 30° position. Subjects fully relaxed their quadriceps and then performed maximal effort knee extension during which, similarly to the concentric phase of the SSC described above, the dynamometer's motor was turned off, and provided resistance through friction. For this contraction mechanical work (W_{con}) was calculated as in the equation above. To investigate the ability to store and re-use elastic energy, positive SSC work and pure concentric work ratio (W_{ssc}/W_{con}) was determined. Because subjects' isometric MVC torque changed over the training period, the post-exercise SSC test was performed with modified

stretch loads and trigger thresholds, which were set according to the current MVCs. In the dynamometric test sessions, in addition to the general warm-up, subjects performed one warm-up trial for each contraction type with a submaximal effort. There were three maximal attempts for each test contraction, and the highest values were included in the data analysis.

2.4. Countermovement jump (CMJ) force

Standing on a force plate (Tenzi, Pilisvorosvar, Hungary, sampling rate: 450 Hz), subjects placed their hands on their hip and performed three maximal effort countermovement jumps with two minutes recovery. Peak ground reaction force was measured and normalized to subjects' body weight.

2.5. Running and walking economy

A spiroergometric system (Cardiovit AT-104, Schiller-Diamed, Hungary) was used for measuring oxygen consumption (VO_2) during the treadmill test for determining RE and WE. The test protocol that we used was similar to that used by Turner et al. [24] in amateur athletes, with some modifications to make its duration and intensity achievable for the untrained females. In our protocol, subjects walked at 0% incline and at 8 km · h⁻¹ velocity for 6 min, and then continued the treadmill test by running at 10 km · h⁻¹ velocity for an additional 6 min. During the test, for safety reasons, ECG signals were continuously monitored and supervised by a physician. The subjects were allowed to interrupt the test if they had any symptoms or any discomfort that would make it impossible for them to continue the test. Because it was expected that after the training interventions subjects use less oxygen in the same test under the same speed and load, improvements in WE and RE were quantified by calculating pre-to-post changes in peak VO_2 during the first (walking) and the second (running) 6-min time intervals.

2.6. Strength training

Both experimental groups performed own-body strength training exercises 3 times per week for 8 weeks. Each training session started with a general warm-up consisting aerobic exercises (aerobics steps and choreography) and regular dynamic and static stretching. In the main part, subjects performed a circuit training. At the end of the session, there was a cool-down, including stretching and breathing exercises. To balance strength improvements in the whole body, in the main part, subjects performed both lower and upper body and core exercises. Furthermore, though low impact SSCs were applied in the SSC group, it is recommended that core stabilization be performed prior to or during a lower-extremity SSC program. The lower body exercises included

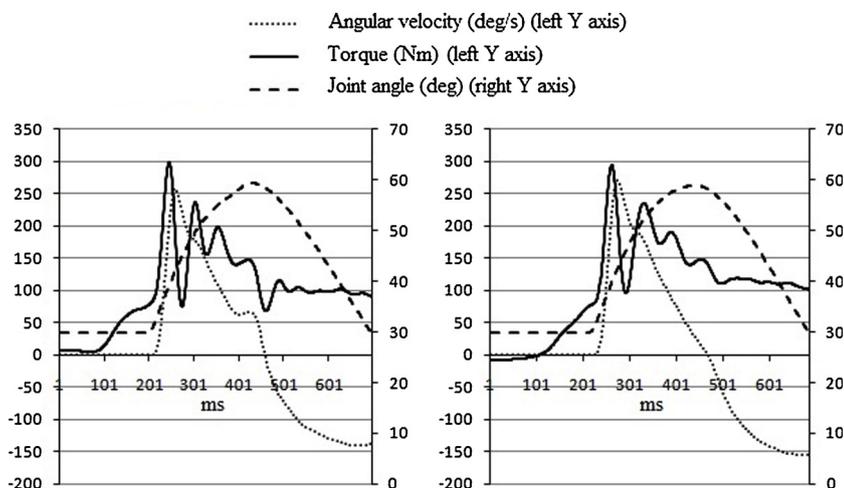


Fig. 2. Representative recording (sampling frequency: 1000 Hz) of the torque (primary Y axis) – angular velocity (primary Y axis) – knee angle (secondary Y axis) – time curve during the stretch-shortening contraction of the knee extensors. Figure demonstrates the pre- (left) and post-exercise (right) curve from a subject with 20% improvement in W_{ssc}/W_{cc} .

dynamic and isometric squats, forward lunges, standing calf raises, side step squats, stationary footwork (steps and sprints). Upper-body and core exercises included crunches, leg raises, plank, back extensions, sit ups, single-leg hip extensions in kneeling position, push-ups, and V sit ups.

The volume was progressively increased every two weeks. Over the 8-week program, three sets were performed constantly, however the repetition for the dynamic exercises increased from 10 to 20, and the duration of the isometric exercises increased from 30 to 60 s. The recovery periods between sets were 2 min throughout the 8 weeks. The duration of the strength training sessions was between 30 and 45 min.

2.7. SSC training

Only the ST-SSC group performed additional SSC exercise, immediately after the main part of the own-body strength training sessions. Subjects executed plyometric exercises such as double-leg ankle hops, double-leg zig-zag jumps, high knee sprints, double-leg and single-leg countermovement jumps (left and right), which have been used safely in a previous studies [24,25]. The number of sets and repetitions increased from 1 to 2 and from 10 to 20, respectively. The number of sets and repetitions were 1 × 10 at week 1 and 2, 2 × 10 at week 3 and 4, 2 × 20 at week 5–8. The number of foot contacts per training session was 50 at week 1 and 2, 100 at week 3 and 4, and 200 at week 5–8. The rest period between sets was kept constantly 2 min over the 8-week exercise program. Subjects were instructed to perform the exercises with maximum effort and with least ground contact time in order to enhance improvements in elastic energy storage and reuse. The SSC sessions lasted 10–20 min.

Both the ST and the SSC exercises were carefully supervised by two physical education teachers, of which one is also qualified as a fitness trainer and the other as a track and field coach. Subjects were provided with proper instructions regarding the exercises and individual corrections in execution techniques were made during exercising and rest intervals to reduce injury risks. None of the subjects reported injury during the program.

2.8. Statistical analysis

Training-induced changes in MVC torque and SSC function were analyzed using a two-way (group × time) analysis of variance (ANOVA) with repeated measures. In case of significant interaction, the Bonferroni correction was used for post-hoc pairwise comparisons. Changes in CMJ force and VO₂ were analysed with a nonparametric Friedman ANOVA at 5% level of random error. To test differences among the variables, Wilcoxon matched-pairs signed-ranks test was used for post-hoc analysis. The post-exercise data in figures are expressed as percent of baseline in each variable.

Statistical power calculations were performed post-hoc for the parametric tests, and the power values were as follows: MVC torque main effect = 0.889, MVC torque group by time interaction = 0.320, Wssc/Wcc main effect = 0.719, Wssc/Wcc group by time interaction = 0.749. Effect sizes (partial eta squared for parametric and Kendall's W for non-parametric tests) are presented in Table 2.

3. Results

The baseline CMJ force mean values (± SEM) for the ST and ST + SSC groups were 26.04 N (± 1.48) and 20.52 N (± 0.65), respectively. The relative changes in CMJ force are presented in Fig. 3. The non-parametric analysis revealed that CMJ force improved only in the ST + SSC group (p < 0.005).

The baseline MVC torque mean values (± SEM) for the ST and ST + SSC groups were 166.86 Nm (± 10.58) and 131.88 Nm (± 9.53), respectively. The two training protocols improved MVC torque uniformly because significant time main effect (F_{1,18} = 11.68, p = 0.003)

Table 2

Partial eta squared (for MVC force and Wssc/Wcc) and Kendall's W values (for CMJ force and peak VO₂) for the representation of effect sizes obtained from the ANOVA and the Friedman ANOVA tests in the measured and calculated variables. CMJ = countermovement jump, MVC = maximal voluntary contraction, Wssc = positive mechanical work during stretch-shortening cycle contraction, Wcc = mechanical work during pure concentric contraction.

Variable	Time main effect	Interaction
MVC torque	0.394	0.052
Wssc/Wcc	0.286	0.289
CMJ force (ST)	0.040	–
CMJ force (ST + SSC)	0.360	–
Peak VO ₂ walking (ST)	0.040	–
Peak VO ₂ walking (ST + SSC)	0.040	–
Peak VO ₂ running (ST)	0.036	–
Peak VO ₂ running (ST + SSC)	0.160	–

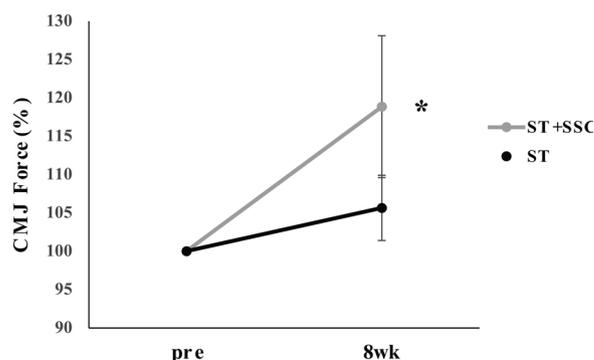


Fig. 3. Relative change in CMJ force (%). Values are mean ± SEM. * Significant difference from baseline (p < 0.05).

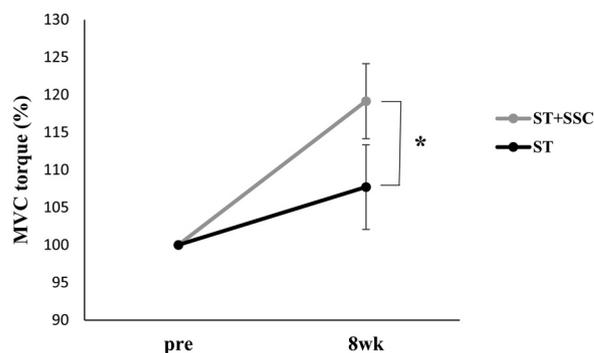


Fig. 4. Relative change in MVC torque (%). Values are mean ± SEM. * Significant time main effect (p < 0.05).

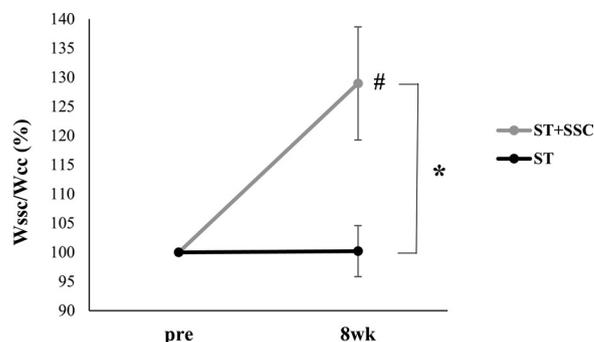


Fig. 5. Relative change in Wssc/Wcc (%). Values are mean ± SEM. # Significant difference from pre value (p < 0.05) revealed by the ANOVA post-hoc analysis. * Significant time main effect (p < 0.05).

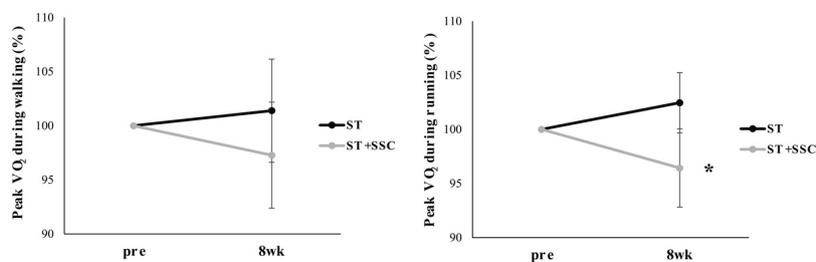


Fig. 6. Relative change in peak VO₂ during walking and running. Values are mean \pm SEM. * Significant difference from baseline ($p < 0.05$).

was found without a group by time interaction (Fig. 4).

The baseline Wssc/Wcc mean values (\pm SEM) for the ST and ST + SSC groups were 1.08 (\pm 0.03) and 0.81 (\pm 0.03), respectively. The relative changes in Wssc/Wcc are presented in Fig. 5. We found significant time main effect with group by time interaction ($F_{1,18} = 7.66$, $p = 0.013$) for Wssc/Wcc. The post-hoc test revealed that Wssc/Wcc significantly improved in the ST + SSC group ($p = 0.016$) and there was no change in the ST group.

During walking, the baseline peak VO₂ (\pm SEM) for the ST and ST + SSC groups were 21.64 (\pm 1.02) and 21.75 (\pm 1.13) ml/kg/min (Fig. 6). During running, the baseline peak VO₂ (\pm SEM) for the ST and ST + SSC groups were 29.62 (\pm 1.22) and 29.59 (\pm 1.38) ml/kg/min (Fig. 6). Peak VO₂ during running reduced significantly only in the ST + SSC group. There was no change in peak VO₂ during walking in any of the groups.

4. Discussion

The main finding in the present study is that ST and ST + SSC training uniformly improved quadriceps MVC torque, however, CMJ force, SSC function, and RE was selectively improved in the ST + SSC group. WE was unaffected by either of the interventions.

MVC torque represents a muscle's maximum contractility, the ability to synchronize motor units, and it is often used to characterize general fitness status. There was a lack of group by time interaction, suggesting that the two training protocols uniformly increased MVC torque. The time main effect revealed a remarkable, 10% improvement. Previous studies have shown that MVC improvements were independent of contraction type used in resistance exercise training [26,12]. Recently, Váczai et al. [14] reported similar MVC strength improvements after 10 weeks of eccentric strength training and SSC training, in a total work-matched protocol in healthy males, suggesting that not the stretch stimulus but the mechanical work regulates MVC strength changes. Time under tension has also been reported previously as a key factor in muscle strength development [27,28], however, this was uncontrolled in our study. Research literature suggests that a wide variety of training stimuli can result in maximum strength development [29–32], and considering that our participants were untrained individuals, the 10% improvement in MVC torque fits within the data reported.

In addition to MVC torque, we also tested unilateral quadriceps SSC function of the participants on a dynamometer. Elastic energy storage and re-use was evaluated using the traditional approach: by determining the ratio of positive work in a single quadriceps concentric contraction with and without a pre-stretch. Our results indicate that only the ST + SSC training was effective in increasing the ability to store and re-use elastic energy. Improvements in elastic energy storage and re-use after ST + SSC training might be explained by multiple factors including neural adaptation, improved stretch reflex, and improved coordination [33–35]. It seems that our single-muscle SSC test was sensitive enough to detect changes in SSC performance after the ST + SSC, and it is in accordance with the CMJ force improvement. CMJ force was measured to evaluate reactive strength in our subjects. CMJ performance is often considered an important marker of fitness

level because it reflects rapid muscle contractility, which is associated with the development of fall risks in later ages, and is a predictor of immobility [36]. CMJ performance is determined by multiple factors including maximum strength, elastic energy storage and re-use, and neural activation pattern [37]. Because quadriceps MVC torque improved similarly in our experimental groups, we suggest that favourable elastic energy storage and re-use contributed to CMJ force improvement in the ST + SSC group. However, myoelectric activity was not measured during the performance tests, therefore we have no evidence whether the plyometric exercises used in the training protocol evoked changes in activation strategies.

Our second hypothesis was set based on the findings of Turner et al. [24], who demonstrated improvements in RE after 6 weeks plyometric exercise training. However, data was limited to the elite runners' population only, who represent sophisticated neuromuscular control and running technique and it was unknown whether SSC exercise is beneficial in the untrained population. Furthermore, it is unclear whether SSC improves WE, and whether own-body resistance exercise alone can improve WE and RE. Partly supporting our hypothesis, we found that RE improved selectively in the ST + SSC group. RE is defined as the magnitude of oxygen consumption at a given running speed. Because running and walking involve the natural sequence of the SSC, the magnitude of oxygen use highly depends on the function of the muscle-tendon complex. More specifically, if muscles are sufficiently activated upon landings, elastic energy storage and re-use is enhanced [38], reducing the muscles' oxygen needs at a given amount of work. The SSC exercise-induced gain in CMJ force and in the ability to store and re-use muscle elastic energy is in accordance with the enhanced contractile efficiency in our ST + SSC group. In contrast, however, we found no change in WE in any of the experimental groups. One explanation is that though walking involves the eccentric-concentric muscle actions, the stretch in the muscle-tendon complex in the eccentric phase was probably not fast enough to evoke stretch-reflexes, contributors to elastic energy storage and re-use. On the other hand, the level of pre-activation has been shown to depend on the magnitude of impact force during SSC tasks [39]. Therefore, because the impact force at touchdown is smaller during walking than during running, the low level of pre-activation could also have prevented the muscle-tendon complex to store and re-use elastic energy enough to detect improved WE.

An important limitation in the present study is that though jumping and running technique may change during an 8-week-long exercise intervention, we were unable to measure changes in jumping and running kinematics as well as neural activation pattern. Another limitation is that though quadriceps is highly involved in walking and running, we quantitatively evaluated elastic energy storage and re-use only in this single muscle group and contribution of other muscles therefore remains unknown. Finally, the limited sample size and the fact that only females were recruited must also be considered.

5. Conclusion

In conclusion, the present data suggest that an 8-week-long own-body ST and ST training with additional SSC exercises produced similar changes in quadriceps MVC torque. However, the additional SSCs

selectively improved CMJ force and quadriceps muscle elastic energy storage and re-use, and RE. Because MVC torque improved similarly in the two groups, improved elastic energy storage and re-use rather than maximum muscle contractility may account for the changes in CMJ force and RE. Fitness instructors, strength specialists, and physical therapists should consider the present data into consideration for understanding the specific effects of SSC exercise training in the young untrained population.

Conflict of interest

The present research work was performed by all listed authors. The authors declare no conflict of interest.

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