Journal of Strength and Conditioning Research Publish Ahead of Print
DOI: 10.1519/JSC.0000000000001870

Intermittent but not continuous static stretching improves subsequent vertical jump performance in flexibility-trained athletes

Gregory C. Bogdanis[a], Olyvia Donti[a], Charilaos Tsolakis[a], Ilias Smilios[b], David J. Bishop [c]

[a]School of Physical Education and Sport Science, University of Athens, Greece

[b]School of Physical Education and Sport Science, Democritus University of Thrace, Greece

[c]Institute of Sport, Exercise and Active Living (ISEAL), College of Sport and Exercise Science, Victoria University, Melbourne, Australia.

RUNNING HEAD: Intermittent and continuous stretching effects on jumping

Corresponding author:

G.C. Bogdanis, PhD

Postal: Faculty of Physical Education and Sports Sciences, 41 Ethnikis Antistasis Str, Daphne, 17237, Athens, Greece.

Email: gbogdanis@phed.uoa.gr, **Tel.** +302107276115

Abstract

This study examined changes in countermovement jump (CMJ) height after an intermittent or a continuous static stretching protocol of equal total duration. *Design:* Sixteen male, elite-level gymnasts performed 90 s of intermittent (3 x 30 s with 30 s rest) or continuous stretching (90 s) of the quadriceps muscle. A single-leg stretching and jumping design was used, with the contra-lateral limb serving as a control. The same individuals performed both conditions with alternate legs in a randomized, counterbalanced order. One leg CMJ height was measured for the stretched and the control leg after warm-up, immediately after stretching, and at regular intervals for 10 min after stretching. Range of motion (ROM) of the hip and knee joints was measured before, after, and 10 min post-stretching. Compared to the control leg, intermittent stretching increased CMJ height by 8.1±2.0%, 4 min into recovery (+2.2±2.0 cm, 95%CI: 1.0-3.4 cm, p=0.001), while continuous stretching decreased CMJ height by 17.5±3.3% immediately after (-2.9±1.7 cm, 95%CI: -2.0 to -3.7 cm, p=0.001) and by 12.0±2.7% one min after stretching (-2.2±2.1 cm, 95%CI: -1.2 to -3.2 cm, p=0.001). The increases in hip (2.9 and 3.6^{o}, p=0.001. d=2.4) and knee joint ROM (5.1 and 6.1^{o}, p=0.001. d=0.85) after the intermittent and continuous stretching protocols were not different. The opposite effects of intermittent vs. continuous stretching on subsequent CMJ performance suggests that stretching mode is an important variable when examining the acute effects of static stretching on performance in flexibility-trained athletes.

Key words: range of motion; countermovement jump; muscle power; muscle stiffness

INTRODUCTION

Over the past two decades a substantial body of research has demonstrated that prolonged static stretching (total duration ▪ 60 s) reduces the ability of muscles to generate power, and that performance reductions may persist for several minutes or hours post stretch (1,5,34). This stretch-induced force and power loss has been attributed to neuromuscular inhibition, and decreased muscle-tendon stiffness due to alterations of the viscoelastic properties of the musculotendinous unit (1,15,21). Based on this evidence, it has been recommended to avoid static stretching before exercise requiring rapid force production (34), and several coaches have reduced or abandoned static stretching as part of the warm-up and replaced it with dynamic stretching (18).

Interestingly, previous cross-sectional studies using professional and national level athletes (10) reported no stretch induced deficit on sprint, agility and jumping ability following an acute bout of static stretching. Therefore, the effect of static stretching on performance may depend on the training background of the subjects (22,30). More importantly, there are studies that either failed to detect impairments in muscle performance after static stretching (10,23), or even reported enhancement of muscle power during sprint or jumping tests, provided that the duration of the stretching bouts were brief (<30 s) (2,3). Such brief stretching durations are more realistic in the sporting environment, since a typical warm-up routine in most sports includes 1-3 sets of shorter duration stretches (10-30 s) interspersed with rest intervals of equal duration while the contra-lateral limb is being stretched (33). Therefore, in training practice, short-duration stretches are applied to each limb in an intermittent fashion and further research is required to determine how this might influence subsequent performance. This is even more important to be examined in well trained athletes who regularly apply stretching routines during training and competition.

Although previous findings support total static stretching duration as an important determinant of the magnitude of stretch-induced muscle performance decrements (6,19,20), there is limited evidence of whether this depends on if stretching is applied in an intermittent or a continuous fashion (20,34). Trajano, et al. (36) compared an intermittent (5 x 1-min stretches) with a continuous stretching protocol of the same total duration (i.e., 5 min) and reported that intermittent stretching induced a greater reduction of torque production (-23.8% versus -14.3%), electromyographic (EMG) activity (-27.1% versus -7.9%), and voluntary activation (-15.9% only after intermittent stretching). Once again, however, the total stretching duration used in this study was much greater than what is commonly used in training practice (6,20). Thus, the purpose of the present study was to examine changes in lower-limb explosive performance after two static stretching protocols of equal stretching time (90 s), performed in either an intermittent (3 x 30-s) or a continuous manner (1 x 90-s), in flexibility-trained athletes.

METHODS

Experimental approach to the problem

To investigate the time course of the effect of stretching on jump height, a single-leg stretching and jumping design was used, with the contra-lateral limb serving as control, while the same individuals performed both conditions (intermittent and continuous stretching) with alternate legs on two separate randomly assigned occasions. It was hypothesized that these two stretching protocols would have different effects on jump performance. Following one familiarization session, subjects performed two experimental sessions. On the first visit, anthropometric measurements were taken and they were familiarised with the testing procedures. On the next two visits, the two main experimental sessions took place one week apart at the same time of day (10:00 a.m.). In one experimental session (intermittent protocol) the stretching protocol included 3 static stretches of 30 s of one leg, with a 30-s rest interval in between, while the other leg served as a control and received no stretching treatment. In the other experimental session, the leg used as the control in the previous visit received the stretching treatment (i.e. one 90-s bout of continuous stretching - continuous protocol), with the other leg serving as a control. The order of the stretching treatment (intermittent or continuous) and the order of the legs (right and left) was randomized and counterbalanced. In both experimental sessions, countermovement jump (CMJ) performance of the stretched and control legs were measured by a single, one-leg CMJ at the following time-points: immediately (10-15 s) after warm-up, immediately (10-15 s) after stretching, and at 1, 2, 3, 4, 6, 8 and 10 min after stretching. Range of motion (ROM) of the hip and knee joints of the stretched leg was measured by two experienced examiners using the modified Thomas test immediately after warm-up, immediately after, and 10 min following stretching. ROM of the hip and knee joints of the control leg was also measured after the warm up and following the last CMJ.

Subjects

Sixteen elite male gymnasts, members of the national team (age: 24 ± 4 y, age range: 19-30 y, training experience: 18 ± 4 y, height: 166 ± 5 cm, body mass: 64 ± 5 kg) took part in this study. They were free of injury and were training six days a week, twice per day (approximately 36 hours/week). They gave informed consent to participate in the study, after a thorough explanation of the testing protocol, the possible risks involved, and the right to terminate participation at will. The study was approved by the University's Institutional Review Board (2254/10-6-2015). All procedures were in accordance with the Helsinki declaration of 1964, as revised in 2013.

Procedures

Prior to each experimental session a standardized warm-up was performed, including 5 min of jogging at a moderate intensity (50-60% of age-predicted maximal heart rate). The training load for the week preceding each main session was recorded and kept similar, while subjects were instructed to have a light training session 24 h prior to performing each main experimental session.

Static stretching procedure.

The stretching movement of the modified Thomas test (hip extension combined with knee flexion while lying on a plinth, with force applied by an investigator) was used to stretch the hip flexor and knee extensor muscles of one leg to the point of discomfort (Fig. 1). This maneuver stretches the knee extensors that significantly contribute to one-leg jump, such as the vastus lateralis and the bi-articular rectus femoris muscles (8), as well as hip flexors that are not directly involved in jumping, such as the iliopsoas muscle. The intensity of the stretching was adjusted based on feedback from the subject to ensure the stretch subjectively achieved 90% of the point of discomfort, where 0 represents "no stretch discomfort" and 100% the "maximum imaginable stretch discomfort" (7,40). The static stretching protocols were applied and controlled by the same strength and conditioning researcher. Subjects were familiar with this stretching movement as they performed it regularly in their daily flexibility programs.

Range of motion measurement

Range of motion (ROM) of the hip and knee joints of the stretched leg was measured using the modified Thomas test (Fig. 1) immediately after warm-up, immediately after and 10 min following stretching. ROM of the hip and knee joints of the control leg was also measured after the warm up and following the last CMJ, in order to avoid the possible influence of static stretching on CMJ performance. Subjects sat at the edge of a plinth, then rolled back and lay supine holding the knee of the non-tested leg to the chest with the arms placed around the tibia, so that the lumbar spine was flat on the table. To avoid pelvic tilt, subjects' hips were firmly strapped on the physiotherapy bed (Fig. 1). The leg under testing was lowered down towards the floor with force progressively applied by an experienced examiner, to induce hip hyperextension and knee flexion, up to the point that each subject could tolerate (point of discomfort). To calculate hip and knee ROM, reflective motion analysis markers were placed on the following anatomical marks: hip (trochanterion), knee (femur-tibia joint line) and ankle (lateral malleolus). The position of the markers was recorded using a digital camera (Casio Exilim Pro EX-F1) placed perpendicular to the plane of motion of the leg, and knee and hip angles were calculated as follows (Kinovea Video Analysis Software, v.0.8.15):

(a) hip extension ROM, i.e. the angle between the horizontal and the line joining the hip and knee markers

(b) knee flexion ROM, i.e. the range of movement of the shank around the knee joint, from an extended knee position (straight knee= 0^{o})

Measurement of single leg CMJ performance

One leg CMJ performance was assessed according to the protocol of Bosco et al. (1983) by measuring flight time from force plate data. Participants were asked to bend their knee to approximately 90 degrees, and to take off until hip, knee and ankle were fully extended, and then land in the same spot keeping their hands on their hips throughout the entire jump. Two CMJs separated by 30 s of rest were performed at baseline, while only one CMJ was performed at each recovery time point. In both experimental sessions, CMJ performance of the stretched and the control legs were measured (Ergojump, Psion XP, MA.GI.CA, Rome, Italy) at the following time-points: immediately (10-15 s) after warm-up, immediately (10-15

s) after stretching and at 1, 2, 3, 4, 6, 8 and 10 min after stretching. Subjects rested while standing between CMJ efforts.

STATISTICAL ANALYSES

Statistical analyses were carried out using SPSS (IBM SPSS Statistics Version 23). To examine the differences in CMJ height a 3-way repeated measures analysis of variance (2 x 2 x 9, ANOVA) was used: leg (2 conditions: stretched vs. control) x stretching protocol (2 conditions: intermittent vs. continuous) x time (9 time points). ROM of the hip and knee joints were examined with separate 2 x 2 two-way repeated measures ANOVA for the control leg (2 testing conditions x 2 time points) and the stretched leg (2 testing conditions x 3 time points), due to the fact that ROM in the control leg was measured only at baseline and after the last CMJ, in order to avoid the possible influence of static stretching on CMJ performance in the control condition. When a significant main effect or interaction was observed ($p<0.05$) a Tukey's post–hoc test was performed. Effect sizes (ES) were determined by partial eta squared (η^2) (small: 0.01 to 0.059, moderate: 0.06 to 0.137, large >0.138). For pairwise comparisons, ES was determined by Cohen's d (small: <0.2, medium: >0.2-0.5, large: >0.8). Test-retest reliability for all dependent variables was assessed by calculating the intraclass correlation coefficient (ICC) using a two-way random effect model. Additionally, the standard error of measurements (SEM) was calculated as the square root of the mean square error term from the ANOVA and was expressed both as an absolute value and as a percentage of the participants' mean scores (coefficient of variation, CV) (38). Data are presented as mean±standard deviation and 95% confidence intervals (95%CI).

RESULTS

There was a 3-way interaction of leg x stretching protocol x time ($p<0.0001$, $\eta^2=0.25$). As shown in Fig. 2 (left panel), the intermittent stretching protocol resulted in an increase in CMJ from the 2nd until the 8th minute of recovery compared with baseline, that peaked 4 min after stretching (+3.8±1.5 cm, 95%CI=+3.1 to +4.5 cm, p=0.0001, Cohen's d=1.3). In contrast, the continuous stretching protocol resulted in a decrease in CMJ performance immediately after (-2.5±1.0 cm, 95%CI= -2.0 to -3.0 cm, p=0.0001, Cohen's d=0.9) and 1 min after stretching (-1.5±1.0 cm, 95%CI= -0.9 to -2.1 cm, p=0.049, Cohen's d=0.5), followed by an increase above baseline 6 min into recovery (+1.7±1.0 cm, 95%CI=+1.2 to +2.2 cm, p=0.001;Cohen's d=0.6; see Fig. 2, left panel). Comparison of the CMJ values between the two stretching protocols at corresponding time points revealed higher scores during the first 4 min of recovery following the intermittent protocol compared with the continuous protocol (Fig. 2, left panel).

For the non-stretched leg (control) CMJ was gradually increased on each subsequent jump from baseline up to the 4th min of recovery (1.6±1.3 cm, 95%CI = +1.0 to +2.3 cm, p=0.001, Cohen's d=0.6; Fig. 2, right panel). Post-hoc comparisons revealed that following intermittent stretching, CMJ was 8.1±2.0% higher compared with the control leg at the 4th minute of recovery (+2.2±2.0 cm, 95%CI = +1.0 to +3.4 cm, p=0.001, Cohen's d=0.7; see Fig. 2, left panel). In contrast, after the continuous stretching protocol, CMJ was 12.0±2.7 to 17.5±3.3% lower for the stretched compared with the control leg immediately after (-2.9±1.7 cm, 95%CI=-2.0 to -3.7 cm, p=0.001, Cohen's d=0.9) and 1 min after stretching (-2.2±2.1 cm, 95%CI=-1.2 to -3.2 cm, p=0.001, Cohen's d=0.8; Fig. 2, left panel). The test-retest reliability of single leg CMJ performance was high (ICC=0.965, p<0.01; SEM=0.62 cm; CV=3.1%; p value of ANOVA= 0.69) as determined in a separate session.

Hip and knee ROM of the control leg remained unchanged during both testing protocols ($p=0.57$ to 1.00). However, the two-way ANOVA for the hip and knee joint ROM of the stretched leg showed significant interaction ($p=0.005$, $\eta^2=0.53$ and $p=0.035$, $\eta^2=0.38$, for the hip and knee joint ROM, respectively). Immediately after the intermittent and continuous stretching protocol, hip joint ROM increased similarly by 2.9 ± 0.8^o (95%CI = 2.3 to 3.5^o, $p=0.001$, Cohen's d=2.8) and 3.6 ± 0.5^o (95%CI = 3.3 to 4.0^o, $p=0.001$, Cohen's d=2.4), respectively. Likewise, knee joint ROM increased similarly after the intermittent and continuous stretching protocol (5.1 ± 1.9^o, 95%CI = 4.2 to 6.1^o, $p=0.001$, Cohen's d=0.85, and 6.4 ± 1.0^o, 95%CI = 5.9 to 6.9^o, $p=0.001$, Cohen's d=0.87, respectively). After the end of the CMJ testing, hip and knee joint ROM partially recovered towards the baseline only in the intermittent stretching condition. In contrast, in the continuous stretching condition, both hip and knee joint ROM remained increased after the jumps (Fig. 3). The test-retest reliability of both ROM measurements was high. For hip extension ROM: ICC=0.946, $p<0.01$; SEM=0.6^o; CV=4.6%; p value of ANOVA= 0.44. For knee flexion ROM: ICC=0.971, $p<0.01$; SEM=1.4^o; CV=1.9%; p value of ANOVA= 0.15.

DISCUSSION

The main finding of this study was that, compared to the control leg, a 3 x 30-s intermittent stretching protocol increased CMJ performance by 8.1%, while a continuous stretching protocol of equal total duration resulted in a transient decrease of CMJ performance of 17.5 and 12.0%**,** immediately after stretch to one minute post stretch, respectively. Thus, it may be suggested that in flexibility-trained athletes, total stretching duration (i.e. 90 s) may not be the main factor determining the effects of stretching on muscle performance (6), since intermittent and continuous stretching produced distinctly opposite changes in CMJ performance. Moreover, CMJ performance was enhanced following the intermittent stretching protocol despite an increase in hip and knee joint ROM that was maintained for 10 min post-stretching.

The novel finding of the present study is that CMJ performance of flexibility-trained athletes increases following intermittent stretching of the lower-limb musculature. This is in apparent disagreement with current practice that advocates against static stretching due to its possible detrimental effect on explosive performance (34,39). However, a recent review (5) concluded that static stretching with total duration of <60 s may have little or no negative effect on force and jump performance. In addition, there are a few studies showing small (2-4%) improvements in muscle power and running speed following static stretching of 4-5 different leg muscle groups, each lasting 10-30 s (3). In line with those studies, the results of the present study showed a large increase in one-leg CMJ performance compared both with baseline as well as with the non-stretched, control leg (Fig. 2).

The increase in CMJ following intermittent stretching may be partially explained by the short duration of each stretching bout (30 s) followed by a 30 s rest interval. A previous study (27) showed that during repeated 90 s stretches, muscle viscoelastic properties were largely affected from the initial 90 s bout, and viscoelastic relaxation of the hamstrings remained for 1 h after stretching. However, when stretching duration of stretching bouts was shorter (3 x 45 s), viscoelastic stress relaxation recovered rapidly in each 30 s rest period between the stretches (25). Thus, in the present study, the combination of a relatively short stretch with a 30 s rest interval may have resulted in maintenance of muscle stiffness, in contrast with the longer (90 s) continuous stretching (21,26,28). A possibly maintained stiffness, in combination with repeated jumping, may partially explain the improved CMJ performance in the first 4 min of recovery following intermittent stretching (Fig. 2).

Another factor contributing to the increase in CMJ performance following intermittent stretching may be the use of single vs. double leg jumps. Due to the phenomenon of bilateral deficit, total work of the hip, knee and ankle joints is between 28 and 58% greater during one leg compared with two-leg jumping (8). Furthermore, muscle activation is also higher and push-off time is about 40% longer during single-leg, compared with two-leg jumping (8). The slower movement, combined with higher muscle load and muscle activation in single-leg, as opposed to double-leg jumping, may result in a potentiating effect with each subsequent jump i.e. an increase in muscle power following a “conditioning” stimulus from each preceding jump (31,35). From the data of the control leg, it is clear that repeated jumping (every 1 min) results in a gradual increase in CMJ performance that was significantly higher than baseline on the 4th min of recovery (Fig. 3). Thus, single-leg CMJ efforts performed every minute serve as a muscle activation stimulus. However, an increase of the rest interval between jumps from 1 to 2 min after the 4th min of recovery resulted in a gradual decline of CMJ performance towards baseline (Fig. 2). The fact that repeated CMJ testing induces by itself a potentiation of jump performance may be a confounding factor in studies examining the effects of an intervention during recovery. However, the design of the present study, where one leg received an intervention and the other served as the control, allowed the calculation of the net effect of the two interventions on CMJ performance, and showed clear and opposite effects of intermittent and continuous stretching.

The finding that a continuous static stretch lasting 90 s reduced subsequent vertical jump performance has been confirmed by several previous studies and has implications for its use immediately before activities requiring speed and power (20,34). The decrease of CMJ performance after continuous stretching protocols has been attributed to the effect of prolonged stretching on mechanical and neural factors that impair effective force transmission and muscle activation, such as decreased muscle activation or altered reflex sensitivity and the storage and utilization of elastic energy (13,21,25,27,36,37,40). A decrease in muscle stiffness following long duration static stretching (27) could increase the electromechanical delay (11), thus reducing CMJ performance. Additionally, a more compliant muscle-tendon unit may result in a decreased sensitivity of muscle spindles possibly reducing the speed of muscle activation and thus power output after stretching exercises (1,15). Viscoelastic deformation of a muscle's parallel elastic components may also influence lateral force transmission and consequently force and power generation (9,25,27). As shown in previous studies, the viscoelastic deformation of the muscle is not only larger when stretching duration is 90 s, but does not recover even after 1 hour, compared with shorter duration stretches, and this may also explain our findings (21,26,28). Recent evidence shows that the increase in muscle compliance after prolonged static stretching may also alter the length-tension relationship, so that the stretch-induced strength decrements are most apparent at a short muscle length (4). A possible shift of the length-tension relationship in the present study implies that muscle performance is affected at the more open knee angles, i.e. the range of motion where the quadriceps muscles exert force during the one-leg vertical jump (8). Finally, larger fatigue during the continuous vs. intermittent stretching may contribute to the results observed in the present study. There is evidence suggesting that static stretching may place a portion of the motor units into a fatigue state, resulting in an increased number of motor units recruited to perform the same submaximal mechanical work compared to no preceding stretching (24,40). Interestingly, muscle fatigue was only observed following continuous static stretching (40 s), compared with equal duration of intermittent stretching (2 x 20 s) (16). In line with this result, Gomes et al. (17) also reported that intermittent stretching (3 sets of 30 s of static stretching interspersed by 30 sec of interval) did not reduce muscle endurance.

The two stretching methods conferred similar increases in hip extension and knee flexion immediately after stretching, thus confirming previous studies reporting that the acute change of ROM following stretching is dependent on total stretch duration (20). Ten minutes after stretching, hip and knee joint ROM in both protocols remained increased, with only hip joint ROM after intermittent stretching exhibiting a small recovery towards baseline (Fig. 3). Thus, although both protocols are equally effective in increasing ROM, continuous stretching may be superior if maintenance of ROM is required. The dissociation of changes in ROM and CMJ performance is an interesting finding of the present study. Although ROM was similarly increased following both stretching protocols, there were opposite effects of intermittent and continuous stretching on subsequent CMJ performance (Fig. 2). Interestingly, Mizuno et al. (29) reported that following 5 min of static stretching, the increase in ROM lasted 30 min, while the decrease in muscle stiffness and isometric peak torque were restored within 10 min.

A few previous studies have shown contralateral effects from stretching on the unstretched limb. For example, Cramer et al. (14) reported decreases in muscle activation from pre to post-stretch in both the stretched and the unstretched leg extensors, suggesting that the stretch-induced neural deficit could be related to a central nervous system inhibitory mechanism. More recently, da Silva et al. (32) also found decreased drop jump height and impulse for the non-stretched limb immediately after an acute static stretching protocol (6 x 45 s with 15 s rest), suggesting a stretch induced central nervous system inhibitory effect. In the present study, the static stretching protocol had no negative effect on the control leg in either type of stretching for the entire recovery period (Fig. 3). Cramer et al. (12), using a similar stretching protocol with the present study (4X30 sec of stretching with 15 sec of rest between stretches), found no effect of static stretching on peak torque in women in both the stretched and the unstretched limb during eccentric muscle actions and associated the lack of the stretch induced deficits with the characteristics of eccentric muscle actions. Single leg CMJ has a large eccentric component where high forces are built up during the eccentric phase and peak at the end of the eccentric/downward movement. Thus, in the present study, the lack of a contralateral effect of stretching may be explained by the significant eccentric component of the single-leg jump, the shorter total duration of the stretching protocol and the training background of the study population.

In conclusion, the application of an intermittent stretching protocol (3 x 30 s) causes a transient increase in CMJ performance, whereas the application of a continuous protocol (90 s) led to a transient decrease of CMJ performance. Although an intermittent and a continuous stretching protocol results in similar increases in ROM, they have opposite effects on CMJ performance in elite athletes; this is despite the fact that total stretching duration is the same. This indicates that the mode of stretching (continuous vs. intermittent) is an important variable when examining the acute effects of static stretching on muscle performance.

Practical applications

The results of this study show that in flexibility-trained individuals an intermittent stretching protocol (3 x 30 s) increases, while a continuous stretching (1 x 90 s) protocol decreases, CMJ performance, despite the same total stretching duration. Thus, although static stretching has generally been shown to be detrimental to subsequent explosive performance, this may not be the case when static stretching is applied in an intermittent manner in flexibility-trained subjects. Due to the fact that CMJ performance following an intermittent stretching protocol peaked 4 min after its application, the combination of intermittent stretching with repeated single-leg jumps may be used as an effective stimulus during warm-up, in order to acutely increase both explosive muscle performance and ROM. The fact that CMJ performance was transiently decreased following 90 s of static stretching, even in these flexibility-trained individuals, suggests that prolonged stretching should be avoided as part of a warm-up performed immediately prior to explosive muscle activities. However, it should be noted that the results of this study may not apply to all individuals since participants in this study were elite gymnasts who were accustomed to long stretching protocols and this may modify muscle responses to acute stretching. The combination of high levels of flexibility and strength of elite gymnasts may render them both more "resistive" to performance reductions following stretching as well as more responsive to CMJ performance enhancement after intermittent stretching.

Acknowledgements

The authors would like to thank the members of the men's Artistic Gymnastics National Team for their participation in this study. In addition, we would like to thank the National Team coaches for their collaboration throughout the study.

REFERENCES

1. Avela, J, Kyröläinen, H, and Komi, P V. Altered reflex sensitivity after repeated and prolonged passive muscle stretching. *J Appl Physiol* 86: 1283–91, 1999.
2. Avloniti, A, Chatzinikolaou, A, Fatouros, IG, Avloniti, C, Protopapa, M, Draganidis, D, Stamboulis, T, Leontsini, D, Mavropalias, G, Gounelas, G, Kambas, A. The Acute Effects of Static Stretching on Speed and Agility Performance Depend on Stretch Duration and Conditioning Level. *J Strength Cond Res* , 2014.
3. Avloniti, A, Chatzinikolaou, A, Fatouros, IG, Protopapa, M, Athanailidis, I, Avloniti, C, Leontsini, D, Mavropalias, G, Tzamurtas, A. The effects of static stretching on speed and agility: One or multiple repetition protocols? *Eur J Sport Sci* 16: 402–8, 2016.
4. Balle, SS, Magnusson, SP, and McHugh, MP. Effects of contract-relax vs static stretching on stretch-induced strength loss and length-tension relationship. *Scand J Med Sci Sports* 25: 764–9, 2015.
5. Behm, DG, Blazevich, AJ, Kay, AD, and McHugh, M. Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy

active individuals: a systematic review. *Appl Physiol Nutr Metab* 41: 1–11, 2015.

6. Behm, DG and Chaouachi, A. A review of the acute effects of static and dynamic stretching on performance. *Eur J Appl Physiol* 111: 2633–51, 2011.

7. Behm, DG and Kibele, A. Effects of differing intensities of static stretching on jump performance. *Eur J Appl Physiol* 101: 587–94, 2007.

8. Bobbert, MF, de Graaf, WW, Jonk, JN, and Casius, LJR. Explanation of the bilateral deficit in human vertical squat jumping. *J Appl Physiol* 100: 493–9, 2006.

9. Bojsen-Møller, J, Schwartz, S, Kalliokoski, KK, Finni, T, and Magnusson, SP. Intermuscular force transmission between human plantarflexor muscles in vivo. *J Appl Physiol* 109: 1608–18, 2010.

10. Chaouachi, A, Castagna, C, Chtara, M, Brughelli, M, Turki, O, Galy, O, Chamari, K, Behm, DG. Effect of warm-ups involving static or dynamic stretching on agility, sprinting, and jumping performance in trained individuals. *J Strength Cond Res* 24: 2001–11, 2010.

11. Costa, PB, Ryan, ED, Herda, TJ, Walter, AA, Hoge, KM, and Cramer, JT. Acute effects of passive stretching on the electromechanical delay and evoked twitch properties. *Eur J Appl Physiol* 108: 301–10, 2010.

12. Cramer, JT, Housh, TJ, Coburn, JW, Beck, TW, and Johnson, GO. Acute Effects of Static Stretching on Maximal Eccentric Torque Production in Women. *J Strength Cond Res* 20: 354, 2006.

13. Cramer, JT, Housh, TJ, Johnson, GO, Miller, JM, Coburn, JW, and Beck, TW. Acute effects of static stretching on peak torque in women. *J Strength Cond Res* 18: 236–41, 2004.

14. Cramer, JT, Housh, TJ, Weir, JP, Johnson, GO, Coburn, JW, and Beck, TW. The acute effects of static stretching on peak torque, mean power output, electromyography, and

mechanomyography. *Eur J Appl Physiol* 93: 530–539, 2005.

15. Fowles, JR, Sale, DG, and MacDougall, JD. Reduced strength after passive stretch of the human plantarflexors. *J Appl Physiol* 89: 1179–88, 2000.

16. Franco, BL, Signorelli, GR, Trajano, GS, and de Oliveira, CG. Acute effects of different stretching exercises on muscular endurance. *J Strength Cond Res* 22: 1832–7, 2008.

17. Gomes, TM, Simão, R, Marques, MC, Costa, PB, and da Silva Novaes, J. Acute effects of two different stretching methods on local muscular endurance performance. *J Strength Cond Res* 25: 745–52, 2011.

18. Hough, PA, Ross, EZ, and Howatson, G. Effects of dynamic and static stretching on vertical jump performance and electromyographic activity. *J Strength Cond Res* 23: 507–12, 2009.

19. Kay, AD and Blazevich, AJ. Reductions in active plantarflexor moment are significantly correlated with static stretch duration. *Eur J Sport Sci* 8: 41–46, 2008.

20. Kay, AD and Blazevich, AJ. Effect of acute static stretch on maximal muscle performance: a systematic review. *Med Sci Sports Exerc* 44: 154–64, 2012.

21. Kay, AD, Husbands-Beasley, J, and Blazevich, AJ. Effects of Contract-Relax, Static Stretching, and Isometric Contractions on Muscle-Tendon Mechanics. *Med Sci Sports Exerc* 47: 2181–90, 2015.

22. Lima, CD, Brown, LE, Wong, MA, Leyva, WD, Pinto, RS, Cadore, EL, Ruas, CV. Acute Effects of Static vs. Ballistic Stretching on Strength and Muscular Fatigue Between Ballet Dancers and Resistance Trained Women. *J Strength Cond Res* , 2016.

23. Little, T and Williams, AG. Effects of differential stretching protocols during warm-ups on high-speed motor capacities in professional soccer players. *J Strength Cond Res* 20: 203–7, 2006.

24. Lowery, RP, Joy, JM, Brown, LE, Oliveira de Souza, E, Wistocki, DR, Davis, GS, Naimo, MA, Zito, GA, Wilson, JM. Effects of static stretching on 1-mile uphill run performance. *J Strength Cond Res* 28: 161–7, 2014.

25. Magnusson, SP, Aagaard, P, and Nielson, JJ. Passive energy return after repeated stretches of the hamstring muscle-tendon unit. *Med Sci Sports Exerc* 32: 1160–4, 2000.

26. Magnusson, SP, Aagard, P, Simonsen, E, and Bojsen-Møller, F. A biomechanical evaluation of cyclic and static stretch in human skeletal muscle. *Int J Sports Med* 19: 310–6, 1998.

27. Magnusson, SP, Simonsen, EB, Aagaard, P, Gleim, GW, McHugh, MP, and Kjaer, M. Viscoelastic response to repeated static stretching in the human hamstring muscle. *Scand J Med Sci Sports* 5: 342–7, 1995.

28. Magnusson, SP, Simonsen, EB, Aagaard, P, and Kjaer, M. Biomechanical responses to repeated stretches in human hamstring muscle in vivo. *Am J Sports Med* 24: 622–8, 1996.

29. Mizuno, T, Matsumoto, M, and Umemura, Y. Stretching-Induced Deficit of Maximal Isometric Torque Is Restored Within 10 Minutes. *J Strength Cond Res* 28: 147–153, 2014.

30. Moltubakk, MM, Eriksrud, O, Paulsen, G, Seynnes, OR, and Bojsen-Møller, J. Hamstrings functional properties in athletes with high musculo-skeletal flexibility. *Scand J Med Sci Sports* , 2015.

31. Sale, DG. Postactivation potentiation: role in human performance. *Exerc Sport Sci Rev* 30: 138–43, 2002.

32. da Silva, JJ, Behm, DG, Gomes, WA, Silva, FHD de O, Soares, EG, Serpa, ÉP, de Barros Vilela Jr, G, Lopes, CR, Marchetti, PH. Unilateral plantar flexors static-stretching effects on ipsilateral and contralateral jump measures. *J Sports Sci Med* 14:

315–21, 2015.

33. Simenz, CJ, Dugan, CA, and Ebben, WP. Strength and conditioning practices of National Basketball Association strength and conditioning coaches. *J Strength Cond Res* 19: 495–504, 2005.

34. Simic, L, Sarabon, N, and Markovic, G. Does pre-exercise static stretching inhibit maximal muscular performance? A meta-analytical review. *Scand J Med Sci Sports* 23: 131–48, 2013.

35. Tillin, NA and Bishop, D. Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. *Sports Med* 39: 147–66, 2009.

36. Trajano, GS, Nosaka, K, Seitz, L, and Blazevich, AJ. Intermittent stretch reduces force and central drive more than continuous stretch. *Med Sci Sports Exerc* 46: 902–10, 2014.

37. Trajano, GS, Seitz, L, Nosaka, K, and Blazevich, AJ. Contribution of central vs. peripheral factors to the force loss induced by passive stretch of the human plantar flexors. *J Appl Physiol* 115: 212–8, 2013.

38. Weir, JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res* 19: 231–240, 2005.

39. Winchester, JB, Nelson, AG, Landin, D, Young, MA, and Schexnayder, IC. Static stretching impairs sprint performance in collegiate track and field athletes. *J Strength Cond Res* 22: 13–9, 2008.

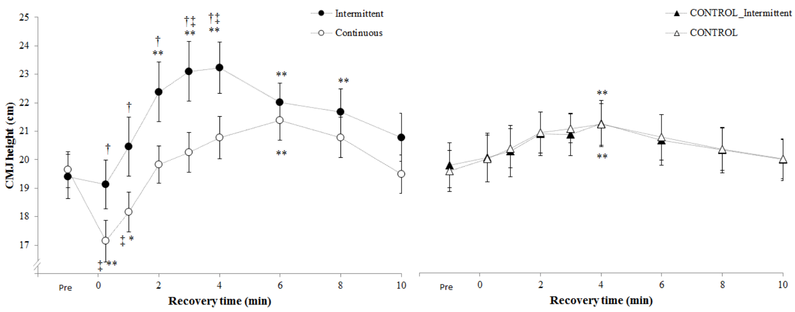
40. Wolfe, AE, Brown, LE, Coburn, JW, Kersey, RD, and Bottaro, M. Time course of the effects of static stretching on cycling economy. *J Strength Cond Res* 25: 2980–4, 2011.

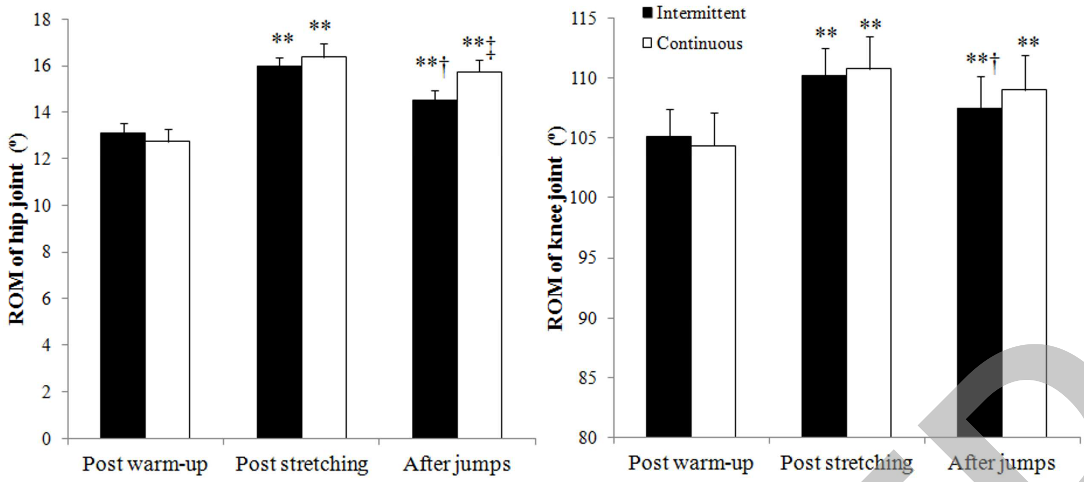
Figure Legends

Figure 1. Position used during the stretching manoeuver (modified Thomas test) and range of motion measurement.

Figure 2. Countermovement jump (CMJ) height during the intermittent and continuous stretching protocols, for the stretched (left panel) and the control leg (right panel). Data are mean ± standard error of the mean. ** and *: $p<0.001$ and 0.05 from baseline (pre), respectively; †: $p<0.001$ from Continuous; ‡: $p<0.001$ from the corresponding CONTROL values.

Figure 3. Range of motion (ROM) of the hip joint (left panel) and the knee joint (right panel) of the stretched leg after the warm-up, after stretching and after all jump measurements during the intermittent and continuous stretching protocols. Data are mean ± standard error of the mean. **: $p<0.01$ from post warm-up; †: $p<0.01$ from post stretching; ‡: $p<0.01$ from the corresponding data point of the continuous stretching protocol.


Intermittent
Continuous
CONTROL_Intermittent
CONTROL
CMJ height (cm)
Recovery time (min)
Recovery time (min)
Pre
Pre



ROM of hip joint (°)
18
16
14
12
10
8
6
4
2
0
**
**
**†
**‡
Post warm-up
Post stretching
After jumps
Intermittent
Continuous
ROM of knee joint (°)
115
110
105
100
95
90
85
80
**
**
**†
**
Post warm-up
Post stretching
After jumps