©Journal of Sports Science and Medicine (2023) **22,** 626-636
http://www.jssm.org DOI: https://doi.org/10.52082/jssm.2023.626

Research article

Acute and Prolonged Effects of 300 sec of Static, Dynamic, and Combined Stretching on Flexibility and Muscle Force

Shingo Matsuo [1]✉, Masahiro Iwata [1], Manabu Miyazaki [2], Taizan Fukaya [3], Eiji Yamanaka [4], Kentaro Nagata [5], Wakako Tsuchida [6], Yuji Asai [1] and Shigeyuki Suzuki [7]

[1] Department of Rehabilitation, Faculty of Health Sciences, Nihon Fukushi University, Handa, Japan; [2] Department of Physical Therapy, Faculty of Medical Science for Health, Teikyo Heisei University, Tokyo, Japan; [3] Department of Physical Therapy, Faculty of Social Work Studies, Josai International University, Togane, Japan; [4] Department of Rehabilitation Medicine, Tokyo Bay Rehabilitation Hospital, Narashino, Japan; [5] Department of International Affairs, Project Division, Japanese Physical Therapy Association, Tokyo, Japan; [6] Health and Medical Research Institute, Department of Life Science and Biotechnology, National Institute of Advanced Industrial Science and Technology (AIST), Kagawa, Japan; [7] Department of Health and Sports Sciences, School of Health Sciences, Asahi University, Mizuho, Japan

Abstract

Static stretching (SS), dynamic stretching (DS), and combined stretching (CS; i.e., DS+SS) are commonly performed as warm-up exercises. However, the stretching method with the greatest effect on flexibility and performance remains unclear. This randomized crossover trial examined acute and prolonged effects of SS, DS, and CS on range of motion (ROM), peak passive torque (PPT), passive stiffness, and isometric and concentric muscle forces. Twenty healthy young men performed 300 sec of active SS, DS, or CS (150-sec SS followed by 150-sec DS and 150-sec DS followed by 150-sec SS) of the right knee flexors on four separate days, in random order. Subsequently, we measured ROM, PPT, and passive stiffness during passive knee extension. We also measured maximum voluntary isometric and concentric knee flexion forces and surface electromyographic activities during force measurements immediately before, immediately after, and 20 and 60 min after stretching. All stretching methods significantly increased ROM and PPT, while significantly decreasing isometric knee flexion force (all $p < 0.05$). These changes lasted 60 min after all stretching methods; the increases in ROM and PPT and the decreases in isometric muscle force were similar. All stretching methods also significantly decreased passive stiffness immediately after stretching (all $p < 0.05$). Decreases in passive stiffness tended to be longer after CS than after SS or DS. Concentric muscle force was decreased after SS and CS (all $p < 0.05$). On the other hand, concentric muscle force was unchanged after DS, while the decreases in surface electromyographic activities during concentric force measurements after all stretching methods were similar. Our results suggest that 300 sec of SS, DS, and CS have different acute and prolonged effects on flexibility and muscle force.

Key words: Warm-up exercise, retention time, range of motion, passive torque, passive stiffness, muscle performance.

Introduction

Static stretching (SS) and dynamic stretching (DS) are commonly performed as warm-up exercises before athletic activities (Smith, 1994; Woods et al., 2007). SS and DS improve flexibility, such as range of motion (ROM), peak passive torque (PPT), and passive stiffness (Goto et al., 2020; Iwata et al., 2019; Matsuo et al., 2019; Mizuno et al., 2013b). Low muscle flexibility (Witvrouw et al., 2003) and high stiffness (Watsford et al., 2010) are associated with a greater risk of muscle injury. Therefore, performing SS and DS as warm-up exercises may reduce muscle injury risk during sports.

Whereas SS and DS have similar positive effects on flexibility, they have distinct effects on sports and muscular performance. Many previous studies have shown that DS improves muscle power, jump height, and sprint time; SS has detrimental effects on these performance measurements (Behm et al., 2016; Behm and Chaouachi, 2011; Kay and Blazevich, 2012; Little and Williams, 2006; Perrier et al., 2011; Yamaguchi and Ishii, 2005). Therefore, DS is recommended as a component of warm-up exercises because of its beneficial effect on athletic performance.

However, SS and DS are usually performed in combination during warm-up exercises. Previous studies have investigated the effects of combined SS and DS on various aspects of sports and muscular performance (Amiri-Khorasani et al., 2016; Amiri-Khorasani et al., 2010; Amiri-Khorasani and Sotoodeh, 2013; Chaouachi et al., 2010; Faigenbaum et al., 2006; Fletcher and Anness, 2007; Hsu et al., 2020; Loughran et al., 2017; Takeda et al., 2020; Torres et al., 2008; Wong et al., 2011). Particularly regarding the effects of combined stretching (CS; i.e., DS+SS) on sports and muscular performance, the positive effects of DS on performance may counteract the negative effects of SS (Amiri-Khorasani et al., 2016; Amiri-Khorasani and Sotoodeh, 2013; Chaouachi et al., 2010; Faigenbaum et al., 2006; Fletcher and Anness, 2007; Hsu et al., 2020; Loughran et al., 2017; Wong et al., 2011). Nevertheless, the stretching method with the greatest effect on flexibility and performance remains unclear. Moreover, stretching routines are typically performed 15 - 60 min before competition or exercise (Woods et al., 2007). Therefore, it is important to investigate the prolonged effects of SS, DS, and CS on flexibility and performance. Matsuo et al. (2019) reported that immediate increases in ROM and PPT and immediate decreases in passive stiffness and isometric muscle force did not differ between 10 sets of 30-s SS and 10 sets of 30-sec DS. Hatano et al. (2019) reported that increases in ROM and PPT and a decrease in isometric muscle force were sustained over 30 min after one set of 300-

Received: 02 May 2023 / Accepted: 25 September 2023 / Published (online): 01 December 2023

sec SS; passive stiffness returned to baseline within 30 min. Mizuno et al. (2013a, 2013b) also reported that the effect of SS on passive stiffness diminished more rapidly than effects on ROM and PPT. Iwata et al. (2019) reported that the effects of 300-sec (10 x 30-sec) DS on ROM and passive stiffness were sustained over 90 min; PPT returned to baseline within 30 min. Accordingly, prolonged changes in flexibility and muscle force might differ between 300-sec SS and 300-sec DS, although effects immediately after SS and DS did not differ. To our knowledge, no studies have directly compared the acute and prolonged effects of SS, DS, and CS in terms of flexibility parameters (e.g., ROM, PPT, and passive stiffness) and muscle force. Additionally, there have been no analyses of these stretching methods in relation to neurophysiological activities, despite previous studies have suggested that the decrease in muscle force after SS was influenced by the changes in neurophysiological activities (Fowles et al., 2000; Kay and Blazevich, 2009; Trajano et al., 2013).

This study compared acute and prolonged effects of SS, DS, and CS (i.e., DS followed by SS or SS followed by DS) on ROM, PPT, passive stiffness, isometric and concentric muscle forces, and surface electromyographic activities. These data could guide the development of recommendations concerning the most appropriate stretching methods for warm-up exercises before athletic activity.

Methods

Study design

We conducted a randomized crossover trial, as illustrated in Figure 1. Prior to the first testing day, all participants attended a familiarization session in which they learned and practiced all stretching methods and measurements. Participants completed measurement sessions on four separate days (1 day for each stretching type). Specifically, they completed four stretching sessions comprising SS alone (SS session), DS alone (DS session), and CS (two CS protocols: 150-sec SS followed by 150-sec DS [SS-DS session] and 150-sec DS followed by 150-sec SS [DS-SS session]) of the right hamstrings for 300 sec. The order of stretching types was randomized. We recorded the ROM of passive knee extension, PPT, passive stiffness, maximum voluntary isometric and concentric knee flexion forces, and electromyographic root mean square (RMS) during force measurements before, immediately after, and 20 and 60 min after stretching (Matsuo et al., 2015). The experiment was performed in a university laboratory where the room temperature was maintained at 26°C (Matsuo et al., 2019; Matsuo et al., 2015). All measurements were performed at the same time of day (± 1 h). The mean testing interval was 17.0 ± 15.0 days (range, 7 - 63 days); there were no consecutive testing days.

Participants

Twenty healthy young men voluntarily participated in this study (mean ± standard deviation: age, 21.8 ± 1.4 years; height, 171.4 ± 6.3 cm; weight, 64.6 ± 10.8 kg; body mass index, 22.0 ± 3.1 kg/m^2). All participants provided written informed consent to take part in the study. The study protocol was approved by the Human Research Ethics Committee of our institution. Exclusion criteria were lower extremity joint contractures, history of back or lower extremity surgery, neurological disorders, current treatment involving hormones or muscle-affecting drugs, ability to completely extend the right knee from a sitting position as described below (i.e., exceptional flexibility), engagement in competitive sports, regular resistance, aerobics, and flexibility training. Participants were asked to avoid vigorous physical activity during the experimental period.

Procedures

Static stretching

As shown in Figure 2a, to perform SS, each participant assumed a standing upright position and placed their right heel (with the leg extended) on a 50-cm-high platform. The participant then reached forward with their arms toward the extended leg while maintaining a proper lordotic curve (Matsuo et al., 2019). SS was performed at a tolerable intensity without pain (Goto et al., 2020; Matsuo et al., 2019; Matsuo et al., 2015). At the SS session, ten 30-sec sets of SS were performed with a 20-sec rest period between each set (Matsuo et al., 2019).

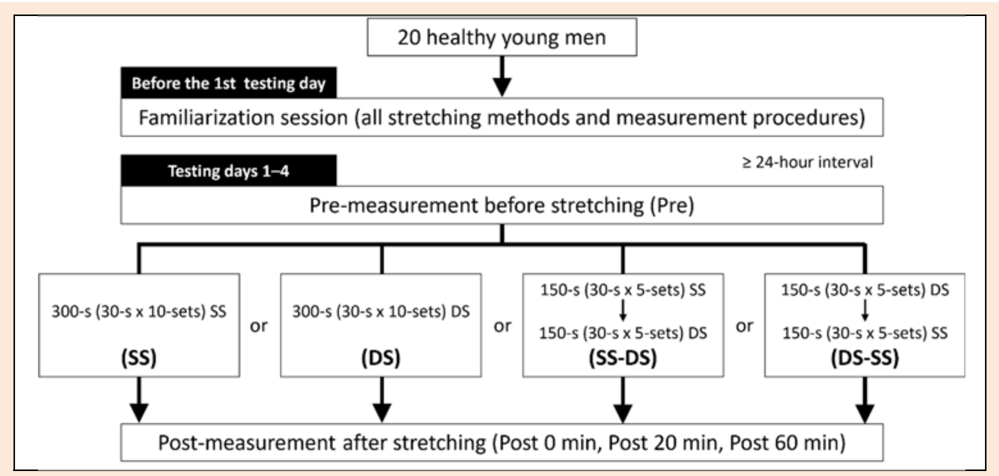

Figure 1. Randomized crossover study design. Prior to the first testing day, all participants attended a familiarization session in which they learned and practiced all stretching methods and measurements. Participants completed measurement sessions on four separate days, one for each stretching type (SS, DS, SS-DS, DS-SS) in random order. SS, static stretching; DS, dynamic stretching; SS-DS, static stretching followed by dynamic stretching; DS-SS, dynamic stretching followed by static stretching.

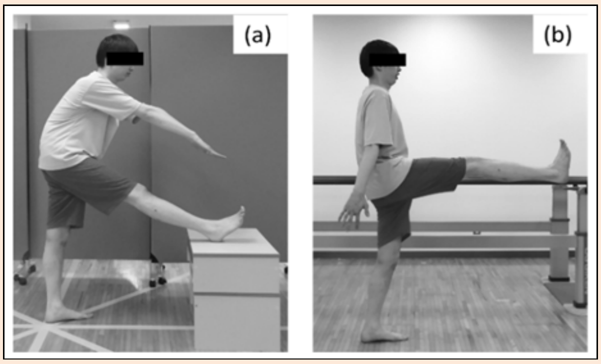

Figure 2. Stretching procedures. (a) Static stretching: Each participant assumed a standing upright position and placed their right heel (with an extended leg) on a 50-cm-high platform. The participant then reached forward with their arms toward the extended leg while maintaining a proper lordotic curve. (b) Dynamic stretching: Each participant assumed a standing upright position, then intentionally contracted the right hip flexors with the knee extended and flexed their right hip joint so that their right leg swung up to the anterior aspect of their body.

Dynamic stretching

As shown in Figure 2b, to perform DS, each participant assumed a standing upright position beside parallel bars and held a parallel bar with their left hand for stability. To stretch the hamstrings, the participant intentionally contracted the right hip flexors with the knee extended and flexed their right hip joint so that their right leg swung up to the anterior aspect of their body (Hough et al., 2009; Iwata et al., 2019; Matsuo et al., 2019; Yamaguchi and Ishii, 2005). The participant performed this dynamic movement every 2 sec. Each exercise was performed five times slowly for practice, then 10 times as quickly as possible without bouncing (Hough et al., 2009; Iwata et al., 2019; Matsuo et al., 2019; Yamaguchi and Ishii, 2005). At the DS session, ten 30-sec sets of DS (15 repetitions of the DS movement in each set) were performed with a 20-sec rest period between each set (Iwata et al., 2019; Matsuo et al., 2019).

Combined stretching

At the two CS sessions, SS and DS were performed as described above. At the SS-DS session, five 30-sec sets of SS followed by five 30-sec sets of DS were performed with a 20-sec rest period between each set. At the DS-SS session, five 30-sec sets of DS followed by five 30-sec sets of SS were performed with a 20-sec rest period between each set.

Dependent variables

The following dependent variables were used to assess the acute and prolonged effects of SS, DS, and CS. We first measured the torque–angle relationship (ROM, PPT, and passive stiffness), then recorded the isometric muscle force, concentric muscle force, and electromyographic RMS during force measurements before, immediately after, and 20 and 60 min after stretching. Considering that warm-up activities prior to SS do not enhance decreases in muscle–tendon stiffness compared with SS alone (Fujita et al., 2018), participants did not perform warm-up activities prior to stretching exercises or testing. All dependent variables, except RMS, were obtained using an isokinetic dynamometer (PrimusRS; BTE Technologies, Hanover, MD, USA); electromyographic RMS was determined by surface electromyography (Biomonitor ME6000; Mega Electronics, Kuopio, Finland). Torque and angle signals from the dynamometer and electrical signals from electromyography were subjected to analog-to-digital conversion (PowerLab 8/35; ADInstruments, Dunedin, New Zealand) and stored in a personal computer.

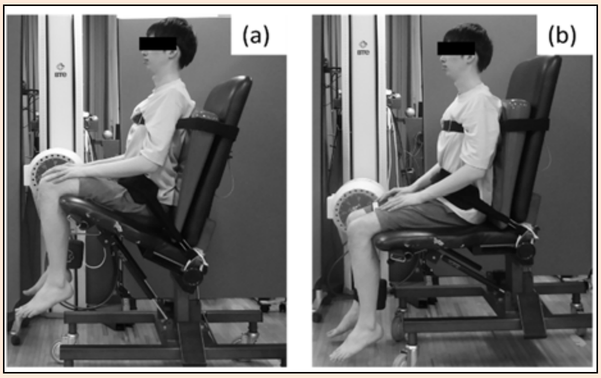

Figure 3. Sitting positions for measurements of dependent variables. (a) Flexed position for measurements of torque–angle relationship and isometric muscle force: Each participant was seated on a chair with the seat maximally tilted and a wedge-shaped cushion inserted between the trunk and the backrest. (b) Horizontal position for the measurements of isometric and concentric muscle force: Each participant was seated on a chair with the seat adjusted parallel to the floor and a wedge-shaped cushion inserted between the trunk and the backrest.

Range of motion, peak passive torque, and passive stiffness

Measurements were performed while the participant assumed a sitting position with their hip joint flexed (Figure 3a), as previously reported (Matsuo et al., 2019; Matsuo et al., 2013; Matsuo et al., 2015). Each participant was seated on a chair with the seat maximally tilted and a wedge-shaped cushion inserted between the trunk and the backrest. The participant's chest, pelvis, and right thigh were stabilized with Velcro straps. The knee joint was aligned with the dynamometer's axis of rotation; the lever arm attachment was placed immediately proximal to the malleolus medialis. In this position, the mean hip and knee flexion angles were 107.1° ± 2.5° and 110.6° ± 2.3°, respectively. While the participant was seated in the chair, their knee was passively extended at 5°/s to the point of maximum knee extension immediately before the onset of pain; torque was continuously recorded during passive knee extension (Matsuo et al., 2019; Matsuo et al., 2013; Matsuo et al., 2015). ROM (in degrees) was defined as the maximum knee extension angle from the initial position (0°); PPT (in Nm) was defined as the torque immediately before the onset of pain (Goto et al., 2020; Matsuo et al., 2019; Matsuo et al., 2015). Passive stiffness (in Nm/°) was defined as the slope of the least-squares regression line calculated from the torque–angle relationship (Matsuo et al., 2019; Matsuo et al., 2013; Matsuo et al., 2015). Passive stiffness was calculated using the same knee extension angle range for all time points. The calculated knee extension angle range was defined as the angle from the 50% maximum knee extension angle to the pre-stretching maximum knee extension angle.

Isometric muscle force

Isometric muscle force (in Nm) was measured in the position used to measure the torque–angle relationship (flexed position; Figure 3a). Isometric muscle force was also measured with the seat adjusted parallel to the floor (horizontal position; Figure 3b) while the participant was seated with hip and knee flexion angles of 85° and 90°, respectively (Matsuo et al., 2015). Isometric muscle force was measured in the flexed position, followed by the horizontal position. Two measurement positions were used because stretch-induced strength loss depends on muscle length (McHugh and Nesse, 2008), and the horizontal position is often used to measure isometric muscle force (e.g., Ford-Smith et al., 2001; Kollock et al., 2010). Each participant was instructed to sit with their arms crossed in front of their chest and generate maximum knee flexion force for 3 sec. They performed this exercise three times with a 45-sec rest period between trials (Matsuo et al., 2015). Verbal encouragement was provided during measurements. Peak torque was recorded for each trial; the mean of the three trials was used in subsequent analysis.

Concentric muscle force

After measurement of isometric muscle force in the horizontal position, concentric muscle force (in Nm) was measured in the horizontal position described above (Figure 3b) using an isokinetic dynamometer (Matsuo et al., 2015). Three maximum voluntary concentric knee flexions were continuously performed at an angular velocity of 60°/s for the range of 85° from a knee-extended position (5°) to a knee-flexed position (90°) with the participant's arms crossed in front of their chest. Verbal encouragement was provided during measurements. Peak torque was recorded for each trial; the mean of the three trials was used in subsequent analysis (Matsuo et al., 2015).

Electromyographic activity

Surface electromyographic activities during maximal isometric and concentric contractions were recorded from medial and lateral hamstrings by a Biomonitor ME6000 (Mega Electronics) with a sampling frequency of 1 kHz. Before electrode placement, the skin under the electrodes was shaved, abraded, and cleaned. For medial hamstring assessment, a pair of Ag/AgCl sensors (Blue Sensor M-00-s; Ambu, Ballerup, Denmark) was placed halfway between the ischial tuberosity and the medial epicondyle of the tibia. For lateral hamstring assessment, another pair of sensors was placed halfway between the ischial tuberosity and the lateral epicondyle of the tibia (Matsuo et al., 2015). Surface electromyography signals were band-pass filtered (8 - 500 Hz). RMS values were calculated using Labchart v8 software (ADInstruments). Time windows for RMS calculation were 3 sec during isometric contraction and 1.416 sec during concentric contraction; ROM was 85° (5 - 90°), and angular velocity was 60°/s during concentric contraction. The mean of three trials for each contraction was used in subsequent analysis.

Test-retest reliability

Test-retest reliabilities for all dependent variables were determined by calculating intra-class correlation coefficients (ICCs) and 95% confidence intervals (CIs) from pre-stretching values for all stretching sessions. The $ICC_{1,1}$ results indicated acceptable reliability (ROM [$ICC_{1,1}$: 0.845, 95% CI: 0.726 - 0.927], PPT [$ICC_{1,1}$: 0.923, 95% CI: 0.857 - 0.965], passive stiffness [$ICC_{1,1}$: 0.896, 95% CI: 0.810 - 0.952], isometric muscle force [$ICC_{1,1}$: 0.905, 95% CI: 0.852 - 0.943], concentric muscle force [$ICC_{1,1}$: 0.880, 95% CI: 0.783 - 0.944], and RMS [$ICC_{1,1}$: 0.748, 95% CI: 0.685 - 0.805]) (Koo and Li, 2016).

Statistical analyses

Sample size estimation was performed using G*Power software (v 3.0.10; Franz Faul, Kiel University, Kiel, Germany). Based on a previous study regarding the acute effects of SS and DS on passive knee extension ROM (Matsuo et al., 2019), the effect size was 0.88; α level was set at 0.05 and power was set at 0.80. Using the Bonferroni post-hoc test to identify a significant difference from the pre-stretching value, the estimated minimum number of participants was 18. Considering the potential for dropout, 20 participants were recruited.

Data normality was assessed using the Shapiro–Wilk test. The results indicated that isometric muscle force in the flexed and horizontal positions, concentric muscle force, and medial hamstring RMS values during concentric muscle contraction were normally distributed. However, the remaining data did not exhibit normal distribution. Parametric tests were applied to normally distributed data; non-parametric tests were applied to the other variables and to the relative changes (in %) for all variables. Changes in dependent variables over time were compared between stretching sessions by two-way repeated measures analysis of variance (RM-ANOVA) (stretching sessions and time) or the Friedman test. When a significant interaction effect or main effect (stretching sessions or time) was identified using two-way RM-ANOVA or the Friedman test, Bonferroni post-hoc analysis was performed to determine significant pairwise differences between sessions at each time point or to reveal differences from pre-stretching values. Analyses were performed using IBM SPSS statistics version 24.0 (IBM Corp., Armonk, NY, USA); the statistical significance threshold was set at $p < 0.05$. Results are expressed as means ± standard deviations.

Results

Range of motion and peak passive torque

ROM and PPT were significantly increased in all stretching sessions immediately and 20 and 60 min post-stretching, compared with pre-stretching (all $p < 0.05$) (Table 1). There were no significant differences in pre-stretching values, post-stretching values, or relative changes in ROM and PPT between stretching sessions.

Passive stiffness

Passive stiffness was significantly decreased in SS-DS and DS-SS sessions immediately and 20 and 60 min

Table 1. Effects of stretching on changes in the range of motion, peak passive torque, and passive stiffness.

Dependent variable	Stretching method	Pre	Post 0 min	Post 20 min	Post 60 min
ROM (°)	SS	86.0 ± 6.4	99.7 ± 6.9 *	96.2 ± 6.2 *	94.9 ± 6.8 *
	Relative change	-	+16.1 ± 3.5%	+12.1 ± 2.7%	+10.5 ± 4.2%
	DS	86.2 ± 7.4	99.0 ± 6.1 *	95.7 ± 5.7 *	94.4 ± 6.8 *
	Relative change	-	+15.2 ± 5.6%	+11.4 ± 5.8%	+9.7 ± 4.7%
	SS-DS	85.4 ± 6.7	99.3 ± 6.7 *	96.2 ± 7.0 *	94.5 ± 7.4 *
	Relative change	-	+16.5 ± 5.9%	+12.8 ± 4.5%	+10.6 ± 3.6%
	DS-SS	85.8 ± 7.2	99.1 ± 7.4 *	96.5 ± 7.8 *	95.2 ± 6.8 *
	Relative change	-	+15.6 ± 5.1%	+12.6 ± 4.6%	+11.1 ± 4.5%
PPT (Nm)	SS	31.1 ± 6.9	37.2 ± 8.8 *	36.2 ± 8.4 *	35.4 ± 8.2 *
	Relative change	-	+19.8 ± 7.2%	+16.6 ± 8.0%	+13.9 ± 7.8%
	DS	31.2 ± 6.1	36.1 ± 6.5 *	36.1 ± 6.9 *	35.0 ± 7.3 *
	Relative change	-	+16.2 ± 11.8%	+16.0 ± 10.7%	+12.0 ± 9.1%
	SS-DS	31.2 ± 6.3	36.0 ± 7.5 *	35.5 ± 8.0 *	35.0 ± 7.5 *
	Relative change	-	+15.5 ± 8.1%	+13.8 ± 6.8%	+12.1 ± 6.7%
	DS-SS	31.2 ± 7.9	36.5 ± 8.1 *	35.6 ± 8.0 *	34.9 ± 7.9 *
	Relative change	-	+18.0 ± 10.0%	+15.0 ± 7.9%	+12.6 ± 9.1%
Passive stiffness (Nm/°)	SS	0.411 ± 0.119	0.367 ± 0.107 *	0.382 ± 0.111 *	0.385 ± 0.124
	Relative change	-	-10.6 ± 7.3%	-7.1 ± 8.5%	-6.7 ± 12.4%
	DS	0.409 ± 0.100	0.357 ± 0.093 *	0.382 ± 0.105 *	0.385 ± 0.132
	Relative change	-	-12.9 ± 6.3%	-6.8 ± 8.9%	-7.3 ± 9.2%
	SS-DS	0.412 ± 0.108	0.346 ± 0.102 *	0.367 ± 0.094 *	0.377 ± 0.108 *
	Relative change	-	-16.0 ± 10.1%	-10.4 ± 8.6%	-8.7 ± 9.6%
	DS-SS	0.410 ± 0.140	0.359 ± 0.098 *	0.368 ± 0.107 *	0.363 ± 0.112 *
	Relative change	-	-11.3 ± 6.9%	-9.3 ± 7.5%	-10.7 ± 10.0%

ROM, range of motion; PPT, passive torque; SS, static stretching; DS, dynamic stretching; SS-DS, static stretching followed by dynamic stretching; DS-SS, dynamic stretching followed by static stretching. Values are expressed as the mean ± standard deviation. *$p < 0.05$ compared with the pre-stretching value.

post-stretching, compared with pre-stretching (all $p < 0.05$) (Table 1). It was also significantly decreased in SS and DS sessions immediately and 20 min post-stretching, compared with pre-stretching (all $p < 0.05$). Passive stiffness tended to be decreased in SS and DS sessions 60 min post-stretching (SS; $p = 0.09$, DS; $p = 0.06$). There were no significant differences in pre-stretching values, post-stretching values, or relative changes in passive stiffness between stretching sessions.

Isometric muscle force

Results were similar between flexed and horizontal positions. Two-way RM-ANOVA revealed no significant interaction effects but showed a significant main effect of time ($p < 0.05$). Isometric muscle force was significantly decreased in all stretching sessions immediately and 20 and 60 min post-stretching, compared with pre-stretching (all $p < 0.05$) (Table 2 and Table 3). There were no significant differences in pre-stretching values, post-stretching values, or relative changes in isometric muscle force between stretching sessions.

Concentric muscle force

Two-way RM-ANOVA revealed no significant interaction effects but showed significant main effects of stretching session and time ($p < 0.05$). Concentric muscle force was significantly decreased in SS and SS-DS sessions immediately and 20 and 60 min post-stretching, compared with pre-stretching (all $p < 0.05$) (Table 4). It was also significantly decreased in DS-SS sessions 60 min post-stretching ($p < 0.05$), and it tended to be decreased immediately ($p = 0.06$) and 20 min post-stretching, compared with pre-stretching ($p = 0.07$). Concentric muscle force in DS sessions did not significantly change.

There were no significant differences in pre-stretching values, immediately and 60 min post-stretching values, or relative changes in concentric muscle force between stretching sessions. However, concentric muscle force was higher in DS sessions than in DS-SS sessions 20 min post-stretching ($p < 0.05$). Additionally, concentric muscle force tended to be higher in DS sessions than in SS-DS sessions 20 min post-stretching ($p = 0.07$).

Electromyographic Activity

Root mean square values during isometric muscle contractions in the flexed position

Medial hamstring RMS values were significantly decreased in SS and DS sessions immediately and 20 and 60 min post-stretching, compared with pre-stretching ($p < 0.05$) (Table 2). They were also significantly decreased in SS-DS and DS-SS sessions immediately and 60 min post-stretching, compared with pre-stretching (all $p < 0.05$); they tended to be decreased 20 min post-stretching (SS-DS; $p = 0.08$, DS-SS; $p = 0.05$).

Lateral hamstring RMS values were significantly decreased in DS sessions 20 and 60 min post-stretching (both $p < 0.05$), and in DS-SS sessions immediately and 20 min post-stretching (both $p < 0.05$), compared with pre-stretching. In SS-DS sessions, they tended to be decreased 20 min post-stretching ($p = 0.06$). There were no significant differences in pre-stretching values, post-stretching values, or relative changes in RMS values between stretching sessions.

Root mean square values during isometric muscle contractions in the horizontal position

Medial hamstring RMS values were significantly decreased in SS-DS sessions 60 min post-stretching, compared with pre-stretching ($p < 0.05$) (Table 3). In DS sessions, they tended to be decreased immediately and 20 min post-stretching, compared with pre-stretching (immediately; $p = 0.08$, 20 min; $p = 0.05$). Lateral hamstring RMS values were significantly decreased in SS and DS sessions 20 min post-stretching, compared with pre-stretching (both $p < 0.05$). Moreover, RMS values in SS sessions 60 min post-stretching and in DS sessions immediately post-stretching tended to be decreased, compared with pre-stretching (SS; $p = 0.08$, DS; $p = 0.08$). There were no significant differences in pre-stretching values, post-stretching values, or relative changes in RMS values between stretching sessions.

Table 2. **Effects of stretching on changes in isometric muscle force and electromyographic activity at the flexed position.**

Dependant variable	Streching method	Pre	Post 0 min	Post 20 min	Post 60 min
Isometric muscle force at the flexed position (Nm)	SS	70.4 ± 16.4	59.3 ± 15.6 *	58.6 ± 14.6 *	58.5 ± 15.0 *
	Relative change	-	-16.1 ± 8.7%	-16.5 ± 11.5%	-16.8 ± 10.0%
	DS	70.6 ± 12.8	60.6 ± 13.5 *	59.3 ± 13.4 *	58.0 ± 14.0 *
	Relative change	-	-14.5 ± 7.7%	-16.5 ± 8.8%	-18.3 ± 10.3%
	SS-DS	67.3 ± 15.5	58.5 ± 15.9 *	57.1 ± 15.1 *	56.6 ± 15.6 *
	Relative change	-	-13.7 ± 7.7%	-15.5 ± 6.6%	-16.5 ± 8.2%
	DS-SS	69.5 ± 16.9	59.1 ± 17.7 *	56.8 ± 17.4 *	59.5 ± 17.4 *
	Relative change	-	-16.0 ± 9.0%	-19.3 ± 7.9%	-15.1 ± 9.9%
RMS values (medial hamstrings) (μV)	SS	257.6 ± 83.1	204.9 ± 58.8 *	193.0 ± 67.8 *	199.0 ± 80.2 *
	Relative change	-	-17.6 ± 16.2%	-23.9 ± 15.4%	-22.1 ± 21.4%
	DS	254.4 ± 107.2	200.4 ± 70.4 *	212.8 ± 93.4 *	208.0 ± 83.2 *
	Relative change	-	-19.3 ± 15.1%	-15.8 ± 17.7%	-16.2 ± 23.0%
	SS-DS	252.9 ± 83.4	200.7 ± 73.2 *	214.2 ± 91.5	203.2 ± 77.2 *
	Relative change	-	-19.3 ± 18.5%	-13.6 ± 23.3%	-17.9 ± 22.7%
	DS-SS	246.8 ± 88.1	210.5 ± 87.3 *	209.5 ± 85.6	201.3 ± 70.1 *
	Relative change	-	-13.1 ± 26.0%	-12.9 ± 27.4	-16.8 ± 18.2%
RMS values (lateral hamstrings) (μV)	SS	233.6 ± 108.0	218.3 ± 75.3	203.1 ± 65.5	198.2 ± 76.2
	Relative change	-	-1.6 ± 23.4%	-8.1 ± 23.0%	-9.4 ± 24.8%
	DS	206.0 ± 68.3	198.2 ± 74.4	167.3 ± 44.3 *	162.9 ± 53.1 *
	Relative change	-	-3.1 ± 22.8%	-14.5 ± 22.7%	-19.6 ± 16.7%
	SS-DS	201.9 ± 39.5	194.4 ± 55.4	180.4 ± 46.0	191.0 ± 54.1
	Relative change	-	-4.5 ± 15.3%	-10.2 ± 18.9%	-4.8 ± 22.0%
	DS-SS	209.6 ± 71.3	179.5 ± 56.0 *	177.9 ± 67.1 *	192.6 ± 69.4
	Relative change	-	-12.0 ± 16.0%	-14.8 ± 19.0%	-7.0 ± 15.7%

RMS, root mean square; SS, static stretching; DS, dynamic stretching; SS-DS, static stretching followed by dynamic stretching; DS-SS, dynamic stretching followed by static stretching. Values are expressed as the mean ± standard deviation. *$p < 0.05$ compared with the pre-stretching value.

Table 3. **Effects of stretching on changes in isometric muscle force and electromyographic ctivity at the horizontal position.**

Dependant variable	Streching method	Pre	Post 0 min	Post 20 min	Post 60 min
Isometric muscle force at the horizontal position (Nm)	SS	86.8 ± 17.1	77.6 ± 15.2 *	79.8 ± 13.7 *	79.4 ± 14.9 *
	Relative change	-	-10.3 ± 7.2%	-7.4 ± 7.3%	-7.9 ± 9.5%
	DS	86.0 ± 13.5	77.8 ± 15.2 *	78.0 ± 14.1 *	77.5 ± 15.0 *
	Relative change	-	-9.9 ± 5.7%	-9.4 ± 7.7%	-10.2 ± 7.9%
	SS-DS	86.0 ± 17.7	77.1 ± 14.2 *	77.4 ± 13.1 *	76.3 ± 14.7 *
	Relative change	-	-9.8 ± 6.9%	-9.1 ± 7.4%	-10.6 ± 8.7%
	DS-SS	85.4 ± 14.1	77.9 ± 14.0 *	77.1 ± 14.3 *	76.5 ± 13.9 *
	Relative change	-	-8.8 ± 6.3%	-9.8 ± 7.2%	-10.3 ± 7.8%
RMS values (medial hamstrings) (μV)	SS	324.4 ± 99.3	292.9 ± 93.6	282.2 ± 104.8	283.9 ± 116.0
	Relative change	-	-8.5 ± 16.2%	-10.4 ± 25.3%	-10.9 ± 26.9%
	DS	314.8 ± 97.8	284.4 ± 77.7	272.6 ± 92.6	270.4 ± 101.3
	Relative change	-	-5.3 ± 28.0%	-11.0 ± 24.3%	-9.4 ± 33.8%
	SS-DS	312.2 ± 99.0	295.1 ± 87.7	289.4 ± 92.2	272.0 ± 90.9 *
	Relative change	-	-3.8 ± 17.4%	-6.4 ± 13.6%	-11.2 ± 18.0%
	DS-SS	313.8 ± 121.9	294.9 ± 108.5	291.9 ± 100.7	290.3 ± 107.4
	Relative change	-	-1.7 ± 25.0%	0 ± 32.7%	-4.0 ± 20.2%
RMS values (lateral hamstrings) (μV)	SS	263.4 ± 115.4	247.0 ± 114.3	238.7 ± 111.9 *	215.9 ± 77.7
	Relative change	-	-6.4 ± 17.4%	-9.5 ± 14.5%	-13.0 ± 22.2%
	DS	231.7 ± 88.5	210.1 ± 79.5	197.3 ± 65.6 *	209.3 ± 75.9
	Relative change	-	-8.1 ± 16.5%	-10.8 ± 20.6%	-7.8 ± 16.1%
	SS-DS	236.7 ± 83.5	222.4 ± 87.9	216.4 ± 73.2	214.4 ± 82.2
	Relative change	-	-6.5 ± 12.8%	-6.2 ± 16.2%	-8.5 ± 16.1%
	DS-SS	237.4 ± 91.0	236.6 ± 106.4	216.7 ± 90.9	213.6 ± 90.5
	Relative change	-	+4.2 ± 45.1%	-5.6 ± 28.2%	-7.7 ± 25.1%

RMS, root mean square; SS, static stretching; DS, dynamic stretching; SS-DS, static stretching followed by dynamic stretching; DS-SS, dynamic stretching followed by static stretching. Values are expressed as the mean ± standard deviation. *$p < 0.05$ compared with the pre-stretching value.

Table 4. Effects of stretching on changes in concentric muscle force and electromyographic activity.

Dependant variable	Streching method	Pre	Post 0 min	Post 20 min	Post 60 min
Concentric muscle force (Nm)	SS	92.0 ± 20.6	88.2 ± 20.1 *	87.5 ± 20.1 *	87.6 ± 20.2 *
	Relative change	-	-4.1 ± 3.7%	-4.9 ± 6.3%	-4.7 ± 4.9%
	DS	91.4 ± 18.6	88.9 ± 18.8	89.7 ± 19.8 †	88.2 ± 19.0
	Relative change	-	-2.8 ± 6.2%	-2.2 ± 6.3%	-3.6 ± 6.9%
	SS-DS	88.4 ± 18.3	84.4 ± 18.3 *	84.9 ± 18.4 *	84.4 ± 17.4 *
	Relative change	-	-4.7 ± 5.8%	-4.0 ± 5.5%	-4.2 ± 6.9%
	DS-SS	88.1 ± 17.6	84.6 ± 16.5	84.5 ± 18.0	84.5 ± 18.3 *
	Relative change	-	-3.4 ± 7.4%	-4.0 ± 7.9%	-4.3 ± 6.3%
RMS values (medial hamstrings) (μV)	SS	356.1 ± 107.2	323.1 ± 93.6 *	306.8 ± 104.6	305.7 ± 106.2 *
	Relative change	-	-8.4 ± 12.1%	-11.8 ± 22.1%	-12.8 ± 19.5%
	DS	365.2 ± 106.7	330.7 ± 96.6 *	322.4 ± 95.7 *	316.2 ± 101.5 *
	Relative change	-	-9.0 ± 11.4%	-11.1 ± 13.0%	-12.2 ± 16.3%
	SS-DS	373.5 ± 120.5	341.6 ± 126.8 *	328.9 ± 113.1 *	329.7 ± 120.9 *
	Relative change	-	-9.0 ± 14.1%	-11.3 ± 14.4%	-11.0 ± 19.0%
	DS-SS	356.3 ± 115.9	313.6 ± 98.7 *	309.3 ± 106.7 *	325.9 ± 107.1 *
	Relative change	-	-11.4 ± 6.3%	-13.0 ± 12.9%	-8.3 ± 10.5%
RMS values (lateral hamstrings) (μV)	SS	288.4 ± 98.9	275.1 ± 107.6	265.8 ± 114.6	252.7 ± 99.7 *
	Relative change	-	-5.4 ± 11.5%	-8.9 ± 17.3%	-12.7 ± 14.4%
	DS	290.8 ± 111.1	251.3 ± 89.5 *	247.9 ± 86.4 *	253.1 ± 98.7 *
	Relative change	-	-11.8 ± 11.8%	-12.8 ± 13.2%	-12.2 ± 11.5%
	SS-DS	278.0 ± 103.0	259.9 ± 90.3	256.6 ± 89.5	256.7 ± 103.3
	Relative change	-	-5.0 ± 10.0%	-5.9 ± 13.9%	-7.1 ± 18.4%
	DS-SS	271.1 ± 100.9	244.6 ± 100.4	241.7 ± 97.6	249.5 ± 110.6
	Relative change	-	-8.4 ± 18.6%	-8.9 ± 24.5%	-6.9 ± 26.7%

RMS, root mean square; SS, static stretching; DS, dynamic stretching; SS-DS, static stretching followed by dynamic stretching; DS-SS, dynamic stretching followed by static stretching. Values are expressed as the mean ± standard deviation. *$p < 0.05$ compared with the pre-stretching value. †$p < 0.05$ compared with the DS-SS session.

Root mean square values during concentric muscle contraction

Two-way RM-ANOVA revealed no significant interaction effects but showed a significant main effect of time for medial hamstring RMS values ($p < 0.05$). Medial hamstring RMS values were significantly decreased in DS, SS-DS, and DS-SS sessions immediately and 20 and 60 min post-stretching, compared with pre-stretching (all $p < 0.05$) (Table 4). They were also significantly decreased in SS sessions immediately and 60 min post-stretching (both $p < 0.05$); they tended to be decreased 20 min post-stretching ($p = 0.07$). Moreover, lateral hamstring RMS values were significantly decreased in SS sessions 60 min post-stretching ($p < 0.05$) and in DS sessions immediately and 20 and 60 min post-stretching (all $p < 0.05$), compared with pre-stretching. RMS values in SS sessions 20 min post-stretching ($p = 0.07$) and in DS-SS sessions immediately and 20 min post-stretching (immediately; $p = 0.08$, 20 min; $p = 0.07$) tended to be decreased. There were no significant differences in pre-stretching values, post-stretching values, or relative changes in RMS values between stretching sessions.

Discussion

This study compared the acute and prolonged effects of SS, DS, and CS on ROM, PPT, passive stiffness, and isometric and concentric muscle forces. The results showed that increases in ROM and PPT and decreases in isometric muscle force after SS, DS, and CS were similar. However, CS tended to have longer effects on passive stiffness, compared with SS and DS. Additionally, concentric muscle force was u nchanged after DS; it decreased after SS and CS.

With regard to flexibility, this study showed that SS, DS, and CS enhanced ROM and PPT; they reduced passive stiffness. Moreover, the effects of all stretching methods on ROM and PPT lasted 60 min after stretching. Compared with CS, SS and DS tended to have shorter effects on passive stiffness; no significant differences were observed in pre-stretching values, post-stretching values, or relative changes between stretching methods. An increase in ROM immediately after SS and DS is attributable to an increase in PPT - caused by changes in pain threshold or stretch tolerance - and a decrease in passive stiffness (Iwata et al., 2019; Matsuo et al., 2019; Mizuno et al., 2013b). The acute and prolonged effects of SS on flexibility in our study are consistent with previous findings (Hatano et al., 2019; Mizuno et al., 2013a; Mizuno et al., 2013b). Changes in flexibility immediately after DS were also consistent with previous findings (Matsuo et al., 2019); the prolonged effects of DS on PPT and passive stiffness differed from previous work in which the effects of DS on ROM and passive stiffness were sustained over 90 min, while PPT returned to baseline within 30 min (Iwata et al., 2019). Our participants were all men, while the previous study included both men and women. Miyamoto et al. (2018) reported that, in men, ROM was associated with passive muscle stiffness and tolerance to muscle stretch; in women, it was associated with tolerance to muscle stretch but not passive muscle stiffness. Therefore, discrepancies between the studies might be related to sex differences.

The longer effects of CS on passive stiffness might arise from differences in stretched tissues. Nakamura et al. (2011) showed that 300 sec of SS decreased muscle–

tendon unit stiffness and muscle stiffness; the decrease in muscle–tendon unit stiffness was caused by the decrease in muscle stiffness. Samukawa et al. (2011) observed proximal displacement of the muscle–tendon junction of the medial gastrocnemius, but no changes in pennation angle or fascicle length, after five 30-sec sets of DS involving antagonist muscle groups contraction. These authors suggested that DS primarily affects tendinous tissues. Thus, SS and DS might have distinct effects on passive muscle–tendon unit stiffness. Compared with SS and DS, CS might have greater effects on the whole muscle–tendon unit, regardless of stretching order. To determine the detailed mechanisms of the effects of stretching on flexibility, further studies are required to investigate how and which tissue is stretched using ultrasonography or shear wave elastography.

With regard to muscle force, this study showed that all stretching methods decreased isometric muscle force after 60 min. However, concentric muscle force was unchanged after DS; no significant differences were observed in pre-stretching values, post-stretching values, or relative changes between stretching methods. There is evidence that prolonged (>30 - 60 sec) SS has detrimental effects on muscle performance (Behm and Chaouachi, 2011; Kay and Blazevich, 2012; Simic et al., 2013). In our study, SS was performed for 300 sec in the SS session and for 150 sec in the SS-DS and DS-SS sessions. The longer duration of SS may have had detrimental effects on isometric and concentric muscle forces in sessions that included SS. The decrease in muscle force after SS might be caused by a reduction in a neural drive, such as a central drive (Trajano et al., 2013), and peripheral electromyographic activity (Fowles et al., 2000; Kay and Blazevich, 2009). The decrease in muscle force after SS might also be due to peripheral force-generating capacity, such as that caused by musculotendinous stiffness and/or associated changes in the muscle length–tension relationship (Fowles et al., 2000; Ryan et al., 2008). In our study, passive stiffness and electromyographic activity were significantly decreased after SS and CS. Therefore, decreases in muscle force after SS and CS might be caused by neurophysiological and mechanical factors.

In this study, passive stiffness and electromyographic activity after DS showed patterns similar to measurements after other stretching methods; however, concentric muscle force after DS was unchanged, while isometric muscle force was significantly decreased. Matsuo et al. (2019) reported that 300-sec DS significantly decreased isometric muscle force, in a manner similar to SS. Moreover, Yamaguchi and Ishii (2014) suggested that explosive performance might be impaired as the volume duration of DS increases. Therefore, the 150-sec or 300-sec DS used in this study might have caused isometric muscle force impairment. However, peak force and power reportedly increased when a longer duration (>90 sec) of DS was performed (Behm et al., 2016; Behm and Chaouachi, 2011). A systematic review article (Behm et al., 2016) suggested that part of the positive effect of DS might result in allowing practice at tasks similar to those in the test measurements, and also suggested that the limited evidence indicate generally inconsequential contraction type-dependent effects of DS on force production. Therefore, similar tasks might have been performed between the DS protocol and concentric muscle force measurements in the present study, although the specific components are unclear. Further studies are required to identify factors that affect isometric and concentric muscle force after stretching, along with the effects of stretching on musculoskeletal biomechanics.

This study had some limitations. First, we did not assess central factors that affect muscle performance. Therefore, future studies should assess central drive parameters, such as percent voluntary activation. Second, we used a long duration of stretching; future studies should compare the effects of our stretching method with a shorter (more common) duration of stretching. Third, we measured overall passive stiffness without considering possible effects on a single component in isolation; such isolation is difficult to perform in human volunteers. Fourth, a potentiation effect was possible during measurements performed after a 45-s rest. However, the mean peak torque from three trials was used for analysis to minimize this effect. Moreover, isometric and concentric muscle forces were measured in a consistent manner at all time points; most post-stretching muscle force values were decreased. Therefore, we presume that any potentiation effect was small. Finally, this study only included men; future studies should include both men and women to improve the generalizability of the findings.

Conclusion

This study showed that changes in ROM, PPT, and isometric muscle force after all stretching methods were similar. However, CS tended to have longer effects on passive stiffness, compared with SS and DS; concentric muscle force only remained unchanged after DS. These results suggest that 300 sec of SS, DS, and CS have different acute and prolonged effects on flexibility and muscle force.

Acknowledgements

We thank Ellen Knapp, PhD, and Ryan Chastain-Gross, PhD, from Edanz (https://jp.edanz.com/ac) for editing a draft of this manuscript. This work was supported by JSPS KAKENHI (Grant Number JP16K01503) and a grant from Nihon Fukushi University Research Institute for Health Sciences. All of the authors declare that there are no potential conflicts of interest. The present study complies with the current laws of the country in which it was performed. The datasets generated and analyzed during the current study are not publicly available but are available from the corresponding author, who was an organizer of the study.

References

Amiri-Khorasani, M., Calleja-Gonzalez, J. and Mogharabi-Manzari, M. (2016) Acute effect of different combined stretching methods on acceleration and speed in soccer players. *Journal of Human Kinetics* **50**, 179-186. https://doi.org/10.1515/hukin-2015-0154

Amiri-Khorasani, M., Sahebozamani, M., Tabrizi, K.G. and Yusof, A.B. (2010) Acute effect of different stretching methods on Illinois agility test in soccer players. *Journal of Strength and Conditioning Research* **24**, 2698-2704. https://doi.org/10.1519/JSC.0b013e3181bf049c

Amiri-Khorasani, M. and Sotoodeh, V. (2013) The acute effects of combined static and dynamic stretch protocols on fitness performances in soccer players. *Journal of Sports Medicine and Physical Fitness* **53**, 559-565.

Behm, D.G., Blazevich, A.J., Kay, A.D. and McHugh, M. (2016) Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy active individuals: a systematic review. *Applied Physiology, Nutrition, and Metabolism* **41**, 1-11. https://doi.org/10.1139/apnm-2015-0235

Behm, D.G. and Chaouachi, A. (2011) A review of the acute effects of static and dynamic stretching on performance. *European Journal of Applied Physiology* **111**, 2633-2651. https://doi.org/10.1007/s00421-011-1879-2

Chaouachi, A., Castagna, C., Chtara, M., Brughelli, M., Turki, O., Galy, O., Chamari, K. and Behm, D.G. (2010) Effect of warm-ups involving static or dynamic stretching on agility, sprinting, and jumping performance in trained individuals. *Journal of Strength and Conditioning Research* **24**, 2001-2011. https://doi.org/10.1519/JSC.0b013e3181aeb181

Faigenbaum, A., Kang, J., McFarland, J., Bloom, J., Magnatta, J., Ratamess, N. and Hoffman, J. (2006) Acute effects of different warm-up protocols on anaerobic performance in teenage athletes. *Pediatric Exercise Science* **18**, 64-75. https://doi.org/10.1123/pes.18.1.64

Fletcher, I.M. and Anness, R. (2007) The acute effects of combined static and dynamic stretch protocols on fifty-meter sprint performance in track-and-field athletes. *Journal of Strength and Conditioning Research* **21**, 784-787. https://doi.org/10.1519/R-19475.1

Ford-Smith, C.D., Wyman, J.F., Elswick, R.K., Jr. and Fernandez, T. (2001) Reliability of stationary dynamometer muscle strength testing in community-dwelling older adults. Archives of Physical Medicine and Rehabilitation **82**, 1128-1132. https://doi.org/10.1053/apmr.2001.24291

Fowles, J.R., Sale, D.G. and MacDougall, J.D. (2000) Reduced strength after passive stretch of the human plantarflexors. *Journal of Applied Physiology* **89**, 1179-1188. https://doi.org/10.1152/jappl.2000.89.3.1179

Fujita, K., Nakamura, M., Umegaki, H., Kobayashi, T., Nishishita, S., Tanaka, H., Ibuki, S. and Ichihashi, N. (2018) Effects of a thermal agent and physical activity on muscle tendon stiffness, as well as the effects combined with static stretching. *Journal of Sport Rehabilitation* **27**, 66-72. https://doi.org/10.1123/jsr.2015-0165

Goto, S., Matsuo, S., Iwata, M., Tsuchida, W., Hatano, G., Kataura, S., Banno, Y., Asai, Y. and Suzuki, S. (2020) Effects of low-intensity and short-duration isometric contraction after static stretching on range of motion, passive stiffness, and isometric muscle force. *Journal of Physical Fitness and Sports Medicine* **9**, 247-255. https://doi.org/10.7600/jpfsm.9.247

Hatano, G., Suzuki, S., Matsuo, S., Kataura, S., Yokoi, K., Fukaya, T., Fujiwara, M., Asai, Y. and Iwata, M. (2019) Hamstring stiffness returns more rapidly after static stretching than range of motion, stretch tolerance, and isometric peak torque. *Journal of Sport Rehabilitation* **28**, 325-331. https://doi.org/10.1123/jsr.2017-0203

Hough, P.A., Ross, E.Z. and Howatson, G. (2009) Effects of dynamic and static stretching on vertical jump performance and electromyographic activity. *Journal of Strength and Conditioning Research* **23**, 507-512. https://doi.org/10.1519/JSC.0b013e31818cc65d

Hsu, F.Y., Tsai, K.L., Lee, C.L., Chang, W.D. and Chang, N.J. (2020) Effects of dynamic stretching combined with static stretching, foam rolling, or vibration rolling as a warm-up exercise on athletic performance in elite table tennis players. *Journal of Sport Rehabilitation* **30**, 198-205. https://doi.org/10.1123/jsr.2019-0442

Iwata, M., Yamamoto, A., Matsuo, S., Hatano, G., Miyazaki, M., Fukaya, T., Fujiwara, M., Asai, Y. and Suzuki, S. (2019) Dynamic stretching has sustained effects on range of motion and passive stiffness of the hamstring muscles. *Journal of Sports Science and Medicine* **18**, 13-20. https://pubmed.ncbi.nlm.nih.gov/30787647/

Kay, A.D. and Blazevich, A.J. (2009) Moderate-duration static stretch reduces active and passive plantar flexor moment but not Achilles tendon stiffness or active muscle length. *Journal of Applied Physiology* **106**, 1249-1256. https://doi.org/10.1152/japplphysiol.91476.2008

Kay, A.D. and Blazevich, A.J. (2012) Effect of acute static stretch on maximal muscle performance: a systematic review. *Medicine and Science in Sports and Exercise* **44**, 154-164. https://doi.org/10.1249/MSS.0b013e318225cb27

Kollock, R.O., Jr., Onate, J.A. and Van Lunen, B. (2010) The reliability of portable fixed dynamometry during hip and knee strength assessments. *Journal of Athletic Training* **45**, 349-356. https://doi.org/10.4085/1062-6050-45.4.349

Koo, T.K. and Li, M.Y. (2016) A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine* **15**, 155-163. https://doi.org/10.1016/j.jcm.2016.02.012

Little, T. and Williams, A.G. (2006) Effects of differential stretching protocols during warm-ups on high-speed motor capacities in professional soccer players. *Journal of Strength and Conditioning Research* **20**, 203-207. https://doi.org/10.1519/R-16944.1

Loughran, M., Glasgow, P., Bleakley, C. and McVeigh, J. (2017) The effects of a combined static-dynamic stretching protocol on athletic performance in elite Gaelic footballers: A randomised controlled crossover trial. *Physical Therapy in Sport* **25**, 47-54. https://doi.org/10.1016/j.ptsp.2016.11.006

Matsuo, S., Iwata, M., Miyazaki, M., Fukaya, T., Yamanaka, E., Nagata, K., Tsuchida, W., Asai, Y. and Suzuki, S. (2019) Changes in flexibility and force are not different after static versus dynamic stretching. *Sports Medicine International Open* **3**, 89-95. https://doi.org/10.1055/a-1001-1993

Matsuo, S., Suzuki, S., Iwata, M., Banno, Y., Asai, Y., Tsuchida, W. and Inoue, T. (2013) Acute effects of different stretching durations on passive torque, mobility, and isometric muscle force. *Journal of Strength and Conditioning Research* **27**, 3367-3376. https://doi.org/10.1519/JSC.0b013e318290c26f

Matsuo, S., Suzuki, S., Iwata, M., Hatano, G. and Nosaka, K. (2015) Changes in force and stiffness after static stretching of eccentrically-damaged hamstrings. *European Journal of Applied Physiology* **115**, 981-991. https://doi.org/10.1007/s00421-014-3079-3

McHugh, M.P. and Nesse, M. (2008) Effect of stretching on strength loss and pain after eccentric exercise. *Medicine and Science in Sports and Exercise* **40**, 566-573. https://doi.org/10.1249/MSS.0b013e31815d2f8c

Miyamoto, N., Hirata, K., Miyamoto-Mikami, E., Yasuda, O. and Kanehisa, H. (2018) Associations of passive muscle stiffness, muscle stretch tolerance, and muscle slack angle with range of motion: individual and sex differences. *Scientific Reports* **8**, 8274. https://doi.org/10.1038/s41598-018-26574-3

Mizuno, T., Matsumoto, M. and Umemura, Y. (2013a) Decrements in stiffness are restored within 10 min. *International Journal of Sports Medicine* **34**, 484-490. https://doi.org/10.1055/s-0032-1327655

Mizuno, T., Matsumoto, M. and Umemura, Y. (2013b) Viscoelasticity of the muscle-tendon unit is returned more rapidly than range of motion after stretching. *Scandinavian Journal of Medicine and Science in Sports* **23**, 23-30. https://doi.org/10.1111/j.1600-0838.2011.01329.x

Nakamura, M., Ikezoe, T., Takeno, Y. and Ichihashi, N. (2011) Acute and prolonged effect of static stretching on the passive stiffness of the human gastrocnemius muscle tendon unit in vivo. *Journal of Orthopaedic Research* **29**, 1759-1763. https://doi.org/10.1002/jor.21445

Perrier, E.T., Pavol, M.J. and Hoffman, M.A. (2011) The acute effects of a warm-up including static or dynamic stretching on countermovement jump height, reaction time, and flexibility. *Journal of Strength and Conditioning Research* **25**, 1925-1931. https://doi.org/10.1519/JSC.0b013e3181e73959

Ryan, E.D., Beck, T.W., Herda, T.J., Hull, H.R., Hartman, M.J., Stout, J.R. and Cramer, J.T. (2008) Do practical durations of stretching alter muscle strength? A dose-response study. *Medicine and Science in Sports and Exercise* **40**, 1529-1537. https://doi.org/10.1249/MSS.0b013e31817242eb

Samukawa, M., Hattori, M., Sugama, N. and Takeda, N. (2011) The effects of dynamic stretching on plantar flexor muscle-tendon tissue properties. *Manual Therapy* **16**, 618-622. https://doi.org/10.1016/j.math.2011.07.003

Simic, L., Sarabon, N. and Markovic, G. (2013) Does pre-exercise static stretching inhibit maximal muscular performance? A meta-analytical review. *Scandinavian Journal of Medicine and Science in Sports* **23**, 131-148. https://doi.org/10.1111/j.1600-0838.2012.01444.x

Smith, C.A. (1994) The warm-up procedure: to stretch or not to stretch. A brief review. *Journal of Orthopaedic and Sports Physical Therapy* **19**, 12-17. https://doi.org/10.2519/jospt.1994.19.1.12

Takeda, K., Iwai, M., Tanabe, S., Koyama, S., Hamauzu, Y., Kumazawa, N., Sakurai, H. and Kanada, Y. (2020) The effects of combined static and dynamic stretching of anti-gravitational muscles on body flexibility and standing balance: A preliminary study of healthy young participants. *Journal of Bodywork and Movement Therapies* **24**, 221-227. https://doi.org/10.1016/j.jbmt.2019.05.011

Torres, E.M., Kraemer, W.J., Vingren, J.L., Volek, J.S., Hatfield, D.L., Spiering, B.A., Ho, J.Y., Fragala, M.S., Thomas, G.A., Anderson, J.M., Hakkinen, K. and Maresh, C.M. (2008) Effects of stretching on upper-body muscular performance. *Journal of Strength and Conditioning Research* **22**, 1279-1285. https://doi.org/10.1519/JSC.0b013e31816eb501

Trajano, G.S., Seitz, L., Nosaka, K. and Blazevich, A.J. (2013) Contribution of central vs. peripheral factors to the force loss induced by passive stretch of the human plantar flexors. *Journal of Applied Physiology* **115**, 212-218. https://doi.org/10.1152/japplphysiol.00333.2013

Watsford, M.L., Murphy, A.J., McLachlan, K.A., Bryant, A.L., Cameron, M.L., Crossley, K.M. and Makdissi, M. (2010) A prospective study of the relationship between lower body stiffness and hamstring injury in professional Australian rules footballers. *American Journal of Sports Medicine* **38**, 2058-2064. https://doi.org/10.1177/0363546510370197

Witvrouw, E., Danneels, L., Asselman, P., D'Have, T. and Cambier, D. (2003) Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. A prospective study. *American Journal of Sports Medicine* **31**, 41-46. https://doi.org/10.1177/03635465030310011801

Wong, D.P., Chaouachi, A., Lau, P.W.C. and Behm, D.G. (2011) Short durations of static stretching when combined with dynamic stretching do not impair repeated sprints and agility. *Journal of Sports Science and Medicine* **10**, 408-416. https://pubmed.ncbi.nlm.nih.gov/24149890/

Woods, K., Bishop, P. and Jones, E. (2007) Warm-up and stretching in the prevention of muscular injury. *Sports Medicine* **37**, 1089-1099. https://doi.org/10.2165/00007256-200737120-00006

Yamaguchi, T. and Ishii, K. (2005) Effects of static stretching for 30 seconds and dynamic stretching on leg extension power. *Journal of Strength and Conditioning Research* **19**, 677-683. https://doi.org/10.1519/15044.1

Yamaguchi, T. and Ishii, K. (2014) An optimal protocol for dynamic stretching to improve explosive performance. *Journal of Physical Fitness and Sports Medicine* **3**, 121-129. https://doi.org/10.7600/jpfsm.3.121

Key points

- We compared the acute and prolonged effects of static, dynamic, and combined stretching on range of motion, peak passive torque, passive stiffness, and isometric and concentric muscle forces.
- After stretching, acute and prolonged increases in the range of motion and peak passive torque, and decreases in isometric muscle force, were not different between stretching methods.
- Decreases in passive stiffness after combined stretching tended to be longer than those after static and dynamic stretching, but they decreased immediately after all stretching methods.
- Concentric muscle force was unchanged after dynamic stretching, but it was decreased after static and combined stretching.

AUTHOR BIOGRAPHY

Shingo MATSUO
Employment
Department of Rehabilitation, Faculty of Health Sciences, Nihon Fukushi University, Handa, Japan
Degree
Ph.D. in Rehabilitation Science
Research interests
Stretching exercise and muscle flexibility
E-mail: matsuo@n-fukushi.ac.jp

Masahiro IWATA
Employment
Department of Rehabilitation, Faculty of Health Sciences, Nihon Fukushi University, Handa, Japan
Degree
Ph.D. in Physical Therapy
Research interests
Exercise physiology, skeletal muscle biology, and mechanobiology
E-mail: iwata-m@n-fukushi.ac.jp

Manabu MIYAZAKI
Employment
Department of Physical Therapy, Faculty of Medical Science for Health, Teikyo Heisei University, Tokyo, Japan
Degree
Ph.D. in Sports Medicine
Research interests
Exercise physiology and human medical engineering
E-mail: m.miyazaki@thu.ac.jp

Taizan FUKAYA
Employment
Department of Physical Therapy, Faculty of Social Work Studies, Josai International University, Togane, Japan
Degree
Ph.D. in health science
Research interests
Exercise physiology and evaluation for physical performance
E-mail: tfukaya@jiu.ac.jp

Eiji YAMANAKA
Employment
Department of Rehabilitation Medicine, Tokyo Bay Rehabilitation Hospital, Narashino, Japan
Degree
M.S. in Physical Therapy
Research interests
Neuromuscular control in human movement
E-mail: yamanaka.eiji@outlook.jp

Kentaro NAGATA
Employment
Department of International Affairs, Project Division, Japanese Physical Therapy Association, Tokyo, Japan
Degree
B.H.S. in Physical Therapy
Research interests
Stretching exercises
E-mail: ngt_kntr_0418@yahoo.co.jp

Wakako TSUCHIDA
Employment
Health and Medical Research Institute, Department of Life Science and Biotechnology, National Institute of Advanced Industrial Science and Technology (AIST), Kagawa, Japan
Degree
Ph.D. in Physical Therapy
Research interests
Molecular biology and human movement
E-mail: w-tsuchida@aist.go.jp

Yuji ASAI
Employment
Department of Rehabilitation, Faculty of Health Sciences, Nihon Fukushi University, Handa, Japan
Degree
Ph.D. in Medicine
Research interests
Postural control and vestibular rehabilitation
E-mail: asai@n-fukushi.ac.jp

Shigeyuki SUZUKI
Employment
Department of Health and Sports Sciences, School of Health Sciences, Asahi University, Mizuho, Japan
Degree
Ph.D. in Medicine
Research interests
Evidence based stretching for exercise and rehabilitation
E-mail: ss.ssjpr@gmail.com

✉ **Shingo Matsuo**
Department of Rehabilitation, Faculty of Health Sciences, Nihon Fukushi University, 26-2 Higashihaemi-cho, Handa, Aichi 475-0012, Japan.