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ORIGINAL INVESTIGATION

Acute Effects of Static Active or Dynamic Active Stretching on Eccentric-Exercise-Induced Hamstring Muscle Damage

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Objectives: To examine whether an acute bout of active or dynamic hamstring-stretching exercises would reduce the amount of muscle damage observed after a strenuous eccentric task and to determine whether the stretching protocols elicit similar responses. ***Design:*** A randomized controlled clinical trial. ***Methods:*** Thirty-six young male students performed 5 min of jogging as a warm-up and were allocated to 1 of 3 groups: 3 min of static active stretching (SAS), 3 min of dynamic active stretching (DAS), or control (CON). All subjects performed eccentric exercise immediately after stretching. Heart rate, core temperature, maximal voluntary isometric contraction, passive hip flexion, passive hamstring stiffness (PHS), plasma creatine kinase activity, and myoglobin were recorded at prestretching, at poststretching, and every day after the eccentric exercises for 5 d. ***Results:*** After stretching, the change in hip flexion was significantly higher in the SAS (5°) and DAS (10.8°) groups than in the CON (–4.1°) group. The change in PHS was significantly higher in the DAS (5.6%) group than in the CON (–5.7%) and SAS (–6.7%) groups. Furthermore, changes in muscle-damage markers were smaller in the SAS group than in the DAS and CON groups. ***Conclusions:*** Prior active stretching could be useful for attenuating the symptoms of muscle damage after eccentric exercise. SAS is recommended over DAS as a stretching protocol in terms of strength, hamstring range of motion, and damage markers.

Keywords: muscle flexibility, muscle stiffness, strength

Hamstring injuries are common in sports activities. The injury rate of hamstring muscles has been reported to be 22% to 34%,[1] with a reinjury rate of 50% within 1 month.[2] Sports activities that can cause injury sustained to the hamstring muscles usually involve rapid acceleration and fast running. The eccentric contraction of the hamstrings to decelerate knee extension during the late swing phase of running activities is believed to be related to such injuries.[1,2] It is important to prevent hamstring muscle injury.

Insufficient warm-up, low flexibility, fatigue, and strength imbalances between quadriceps and hamstrings are believed to be risk factors of hamstring injury.[3,4] Traditionally, to enhance muscle flexibility and performance and to prevent muscle damage, stretching is performed as part of a warm-up routine before training and competition.[3,4] The common types of stretching include static stretching (SS), ballistic stretching, and proprioceptive neuromuscular facilitation. Although SS is believed to be easy and safe,[4] evidence to support the efficacy of SS in reducing injury risk is limited.[4] In addition, evidence suggests that SS, ballistic stretching, and proprioceptive neuromuscular facilitation may decrease lower-limb performance.[5] Presumably, active and rhythmic exercise through the full range of motion (ROM) during dynamic active stretching (DAS) can stretch and strengthen the target muscle.[5,6] It has been reported that DAS can increase the concentric and eccentric peak torque and the electromyographic amplitude of the leg extensors and flexors.[7] These mechanisms are related to elevated muscle and core temperature (CT) and heart rate (HR), greater neuromuscular activity,[8] increased number of cross-bridge formations, and regulation of optimal fiber length.[9]

Despite positive reports on DAS from the literature, it remains uncertain whether an acute bout of active stretching exercise can attenuate hamstring muscle damage induced by maximal eccentric exercise. In addition to DAS, we believe that static active stretching (SAS) may have similar positive effects. Unlike traditional static hamstring stretching (eg, performing a hurdler stretch in a non-weight-bearing position), the SAS was performed in a standing, weight-bearing position (cocontraction of knee flexors and extensors). Furthermore, the SAS technique maintains the pelvis in an anterior tilt position, which results in greater tension on the hamstring musculotendinous unit and increases the hamstring-stretching effect.[10] To our knowledge, no study has examined the acute stretching effects of DAS or SAS on hamstring muscle flexibility/contraction and eccentric-exercise-induced muscle damage. Our first hypothesis was that SAS and DAS would result in significant increases in muscle flexibility/contraction before eccentric exercise as compared with a control group. The second hypothesis was that SAS and DAS would reduce the susceptibility of the hamstring muscle to damage after maximal eccentric exercise as compared with the control group. The third hypothesis was that there would be no significant difference in muscle flexibility/contraction or muscle damage between DAS and SAS.

Methods

Subjects

The sample-size estimate was based on previous studies. A sample size of 10 subjects in each group is known to be sufficient to demonstrate improvement in leg-flexor muscle strength and ROM of hip flexion in an active-stretching protocol as compared with controls.[7,11] Based on an α level of .05, a power of .8, and the 20% subject dropout

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rate, 12 subjects per group were recruited. Thirty-six young male students (age 20.6 ± 2.4 y, height 172.3 ± 4.9 cm, weight 65.8 ± 8.8 kg) with limited passive straight-leg elevation, defined as hip-flexion ROM of less than 80°,[12] and no recreationally active, current regular resistance, aerobic, or flexibility training were recruited from a university. Exclusion criteria were a history of lower-extremity injury, neurological disorder, and/or lower back pain. Subjects were assigned to 1 of 3 groups (n = 12 per group), control (CON), SAS, or DAS, by matching the baseline maximal voluntary isometric contraction (MVIC) strength of the hamstring muscles, tested by an isokinetic dynamometer. All participants provided written informed consent before testing. This study was approved by the ethics committee on human research of the university (approval number: 1010030). All subjects were asked to refrain from performing any vigorous physical activity or taking anti-inflammatory medicine or nutritional supplements during the experimental period.

Design

Before stretching (pre-ST), all outcome criteria (including HR, CT, muscle stiffness, ROM, soreness, MVIC, plasma creatine kinase [CK] activity, and myoglobin [Mb] concentration) were recorded for each subject. Then in the SAS and DAS groups, the hamstring in the dominant leg was stretched after 5 minutes of jogging on a treadmill at 6.4 km/h with a grade of 1%. The CON group only jogged for 5 minutes. After jogging and jogging/stretching, the subject sat with both knees flexed and the legs hanging from the chair. The same outcome measures were obtained at poststretching (post-ST). After post-ST, an eccentric-exercise protocol was applied for each subject. The time interval between the stretching intervention and the eccentric exercise protocol was less than 15 minutes. Criterion outcome measurements were obtained immediately after the eccentric-exercise protocol (D0) (except plasma CK and Mb) and every day afterward for 5 days (D1, D2, D3, D4, and D5), while HR and CT measures were only recorded at pre-ST and post-ST (Figure 1). All outcomes were measured at the same time of day each day.

Stretching Protocol

SAS is based on reciprocal inhibition between agonistic and antagonistic muscles. The exercise was modified from a previous study.[13] First, subjects were instructed to take a dominant-leg stepping-forward lunge position in a standing position with the pelvis tilted anteriorly. The lunge involved rotating the trunk and using the hand to reach gently to the opposite toes of the dominant leg, and the knee was extended simultaneously to stretch the hamstring muscles to the point of discomfort without pain.[13] The stretch was maintained for 15 seconds, followed by 15 seconds of rest. The stretching was performed for 6 sets (Figure 2[A]).

The DAS was similar to that used in a previous study.[7] First, subjects were instructed to raise the arms horizontal to the floor, with the pelvis tilted anteriorly. Second, they were instructed to actively swing the dominant leg forward with hip flexion and knee extension to allow the toes to approach the hands to the point of discomfort without pain. These stretches were performed in 15 rhythmic repeated movements per set for 6 sets, with 15 seconds of rest between sets. To maintain similar stretching intensities in the DAS and SAS groups, the stretching of the DAS group was set to a rhythm of 60 beats/min using a metronome (Seiko, DM70 Digital Metronome). Thus, the stretching intensity of 15 seconds for 6 sets of SAS was comparable to 15 rhythmic, repeated movements (1 movement/s) for 6 sets of DAS (Figure 2[B]).

Eccentric Exercise

After each intervention, all subjects performed 6 sets of 10 maximal eccentric contractions of the dominant-leg knee flexors on an isokinetic dynamometer.[3] The subjects were instructed to contract

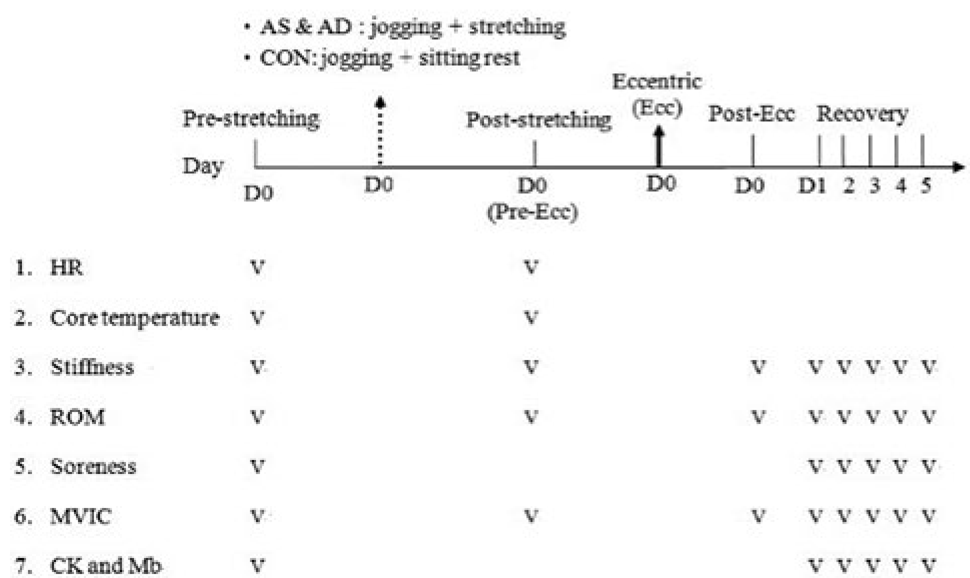

Figure 1 — Participant flow diagram. The study consisted of baseline measurement (prestretching), 1 bout of stretching interventions (CON, AS, AD), poststretching measures, maximal eccentric exercise (ECC), and post-ECC measures. The outcome measures included heart rate (HR), core temperature, maximal voluntary isometric contractions (MVIC), range of motion (ROM), muscle stiffness, muscle soreness, plasma creatine kinase (CK) activity, and myoglobin (Mb) concentration. The time points of these measures are indicated by the letter *V* (pre-ST, post-ST, immediately before ECC [pre-ECC], immediately post-ECC [D0], and D1–D5 after exercise). The sequence of outcome measurement was HR first, followed by core temperature, muscle stiffness, ROM, soreness, MVIC, CK, and Mb. Abbreviations: AS, static active stretching; AD, dynamic active stretching; CON, control.

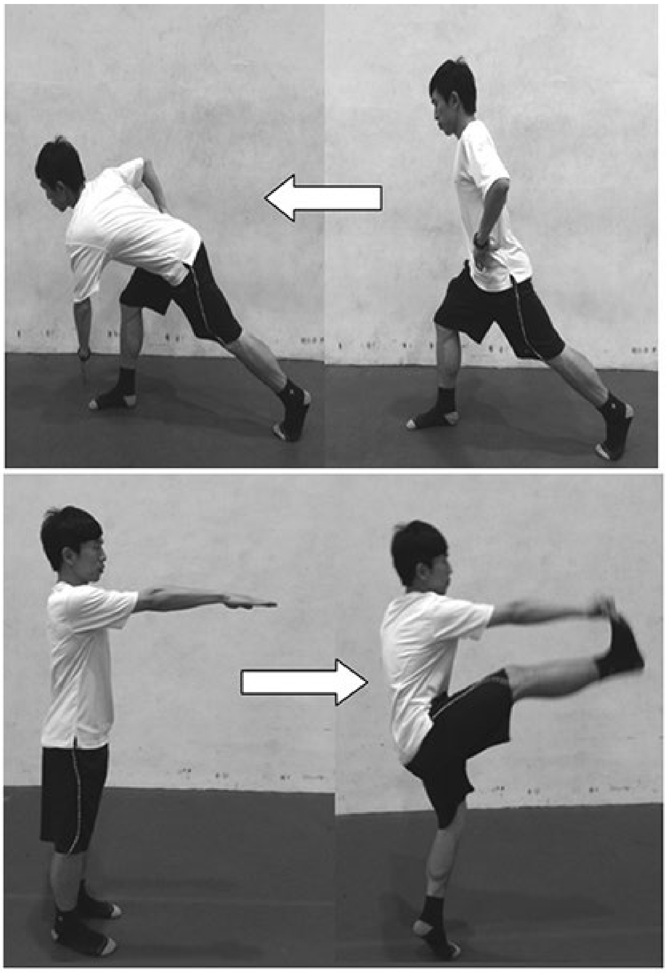

Figure 2 — The 2 types of active stretching exercise for the hamstring muscles. (A) Static active stretching: 6 sets of 15 seconds with 15 seconds of rest between sets. (B) Dynamic active stretching: 15 repetitions (set at a rhythm of 60 beats/min) per set for 6 sets, with a rest period of 15 seconds between sets.

the knee flexors maximally to resist the knee-extending action of the dynamometer, which moved the knee joint from the 110° to the 0° position at an angular velocity of 30°/s. This was repeated 10 times, and a 1-minute rest was given between sets, for a total of 6 sets. The Biodex isokinetic dynamometer software was used to determine isokinetic peak torque and work (the area under the torque curve) of each contraction. The mean torque of each set was obtained and used for subsequent analysis.

Criterion Measures

Three MVICs of hamstring muscle were determined on an isokinetic dynamometer (Biodex System Pro 3, Biodex Medical Systems, Inc, Shirley, NY). Each subject lay prone on the platform of the dynamometer with the upper and lower back regions and the contralateral leg strapped to the platform. The lateral condyle of the femur was aligned with the rotation axis of the dynamometer, and the pad of the dynamometer's lever arm was secured around the ankle and the base of the pad approximately 5 cm proximal to the malleoli.[3] Each MVIC at 30° knee flexion, with verbal encouragement, was maintained for 5 seconds, with rest intervals of 45 seconds.

Hamstring muscle stiffness was quantified by a myotonometer (Neurogenic Technologies, Inc, Missoula, MT), a computerized meter-type device for measuring relaxed muscle-stiffness levels. Using the myotonometer to measure muscle stiffness has been demonstrated to be valid and reliable.[14] The subject lay prone on a padded table, and the pelvis was stabilized by a second examiner. Then the head of the myotonometer probe was placed by an examiner along the longitudinal axis of the biceps femoris muscle of the dominant leg at 50% of the distance from the ischial tuberosity to the medial epicondyle of the tibia. The tissue was displaced at 8 force increments of probe pressure (0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00 kg), and computational software created force-displacement curves (area under the curve [AUC], referring to the measure of passive muscle stiffness). A muscle with lower stiffness (higher AUC) produced a force-displacement curve with a sharper slope than did a muscle with higher stiffness (lower AUC).[15]

Hamstring flexibility was evaluated using passive straight-leg raises (SLR).[3,15] The subject lay supine on a padded table, and both the waist and the nonstretched leg were fixed by a strap. The first examiner held the subject's dominant leg and moved the leg to the position where the subject felt a mild sensation of pain, and a digital inclinometer (inclinometer, Model # A800, Jin-Bomb Inc, Kaohsiung, Taiwan) was placed over the distal tibia. The nonstretched leg was fully extended by a strap, and the second examiner held the pelvis to prevent posterior rotation. This test was repeated 3 times, and the mean of 3 measures was used for analysis.[3,15]

Hamstring muscle soreness was assessed using a 0- to 100-mm (0 = *no soreness,* 100 = *extremely sore*) visual analog scale. Subject reported scores on the scale from sitting on the chair to standing up and walking.[16] HR and CT were monitored by Polar Electro (Oy, Finland) and a tympanic thermometer (TH809 infrared ear, Radiant Innovation Inc, Hsin Chu City, Taiwan), respectively, at pre-ST and post-ST.

For muscle damage measures, ~10 mL of venous blood was collected in a plasma-separation tube by venipuncture from the cubital fossa region. Blood samples were taken from subjects for a determination of plasma CK activity and Mb concentration. Plasma Mb concentration was measured by an automated clinical chemistry analyzer (Model Elecsys 2010, F. Hoffmann-La Roche Ltd, Tokyo, Japan) using a commercial test kit (Roche Diagnostics, Indianapolis, IN, USA). Normal ranges for CK and Mb are 15 to 110 IU/L and 6 to 85 μg/L, respectively.[17]

Statistical Analyses

All statistical analyses were conducted using SPSS 17.0. The reliabilities of passive SLR, MVIC, and muscle stiffness (AUC) were analyzed by intraclass reliability coefficient. The Shapiro-Wilk test was used to confirm normality of the data. If the results showed a normal distribution, ANOVA was used. Otherwise, nonparametric tests were applied. For the first hypothesis, 2-way repeated ANOVA (3 experimental treatments, CON vs SAS vs DAS, and 2 times, pre-ST and post-ST) was used to test the effect of active stretching on each outcome except plasma CK, Mb, and muscle soreness. For the second hypothesis, 2-way repeated ANOVA (3 experimental treatments, CON vs SAS vs DAS, and time series, pre-ST, post-ST, D0, D1, D2, D3, D4, and D5 after eccentric exercise) was used to test the muscle injury of active stretching on outcomes of interest (MVIC, passive SLR, AUC, soreness, and CK and Mb concentrations in the blood). For the third hypothesis, the ANOVA analysis indicated whether there were significant differences in muscle contraction/damage between DAS and SAS. In addition, the eccentric load among the 3 groups was tested. The alpha level was set at .05.

Results

The intraclass reliabilities of subjects' ROM, MVIC, and AUC were .93, .91, and .94, respectively. Before the stretching exercises, no significant differences in HR, CT, MVIC, stiffness, or ROM were found among the groups ($P > .05$). After stretching exercises, HR increased significantly for the 3 groups (CON 27.8 ± 2.2 beats/min, 41.5%; SAS 41.3 ± 4.2 beats/min, 61.4%; DAS 79.5 ± 6.4 beats/min, 120.3%; $P < .001$). The increase in HR in the DAS and SAS groups was significantly higher than that in the control group. The increase in HR in the DAS group was significantly higher than that in the SAS group. There were no CT differences among the groups (CON 36.9 ± 0.1, SAS 36.6 ± 0.1, DAS 36.5 ± 0.1; $P > .5$). ROM decreased significantly in the CON (–4.1° ± 1.1°, –10%) group and increased significantly in the SAS (5.0° ± 0.4°, 12%) and DAS (10.8° ± 0.4°, 27%) groups after the stretching exercise. ROM of the DAS and SAS groups increased significantly relative to the CON group. There was no significant difference in ROM between the SAS and DAS groups. Muscle stiffness decreased significantly more in the DAS group than in the SAS or CON groups after the stretching exercise (AUC increased by 1.0 ± 0.3, 5.6% for DAS, while it decreased by –1.2 ± 0.3, –6.7% for SAS and –1.0 ± 0.3, –5.7% for CON). MVIC decreased significantly in the CON (–9.6 ± 2.4 Nm) and DAS (–13.4 ± 2.1Nm) groups after the stretching exercise. The MVIC was significantly smaller in the CON and DAS groups than in the SAS group.

The average peak torques (CON 93.45 ± 3.2, SAS 100.1 ± 2.3, DAS 95.8 ± 3.1) and work (CON 113.45 ± 3.2, SAS 122.1 ± 2.3, DAS 118.8 ± 3.1) of 10 lengthening contractions of each set during the 6 sets showed no significant differences among the groups ($P > .05$). Both peak torque and work decreased significantly over 6 sets compared with the first set ($P < .001$) (Figure 3).

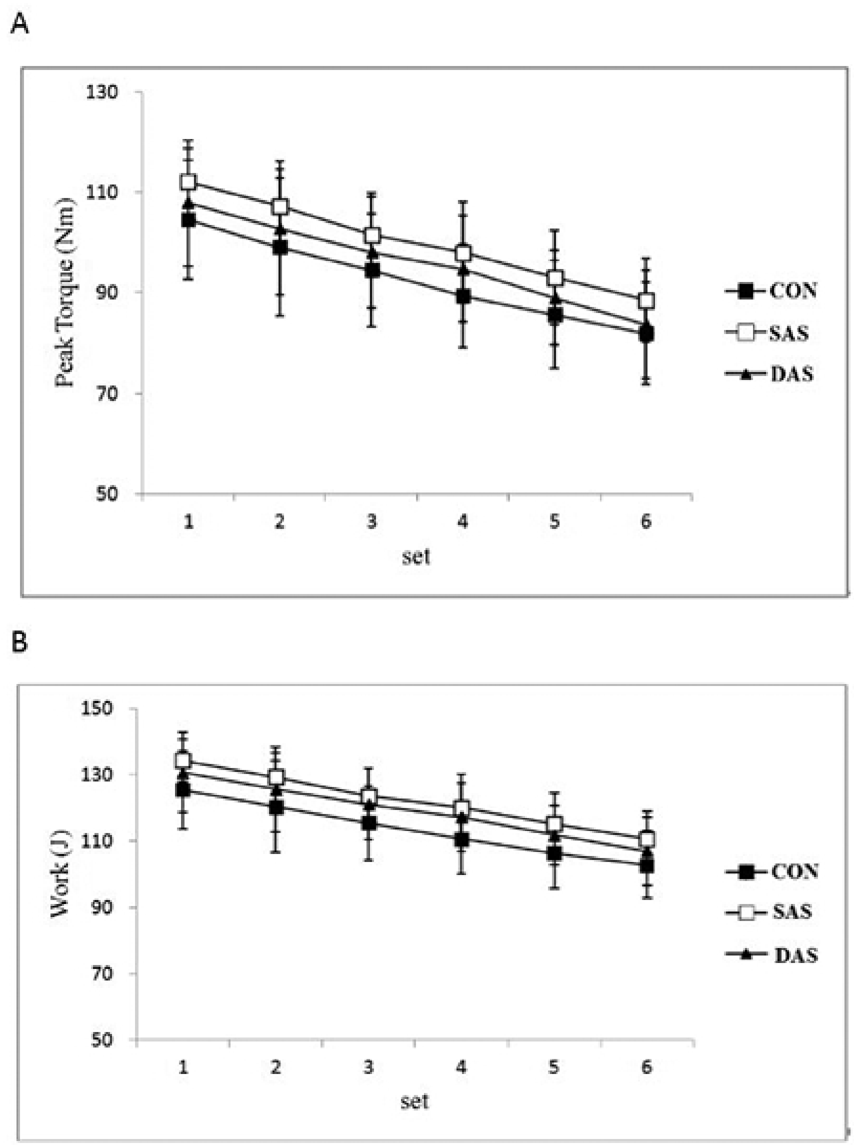

Figure 3 — (A) Peak torque and (B) work over 6 sets of 1 maximal eccentric contraction of the knee flexors for control (CON), static-active-stretching (SAS), and dynamic-active-stretching (DAS) groups. No significant differences among groups.

The mean values for MVIC are reported in Figure 4(A). For MVIC, a significant 2-way interaction (time × intervention) was noted ($P < .001$). Subsequently, the effects of the 3 interventions were investigated separately. The MVIC in the CON and DAS groups decreased significantly (D0–D5 and D0–D4, respectively) after eccentric exercise. In addition, the MVIC after eccentric exercise of the SAS group was significantly better than those of the DAS and CON groups.

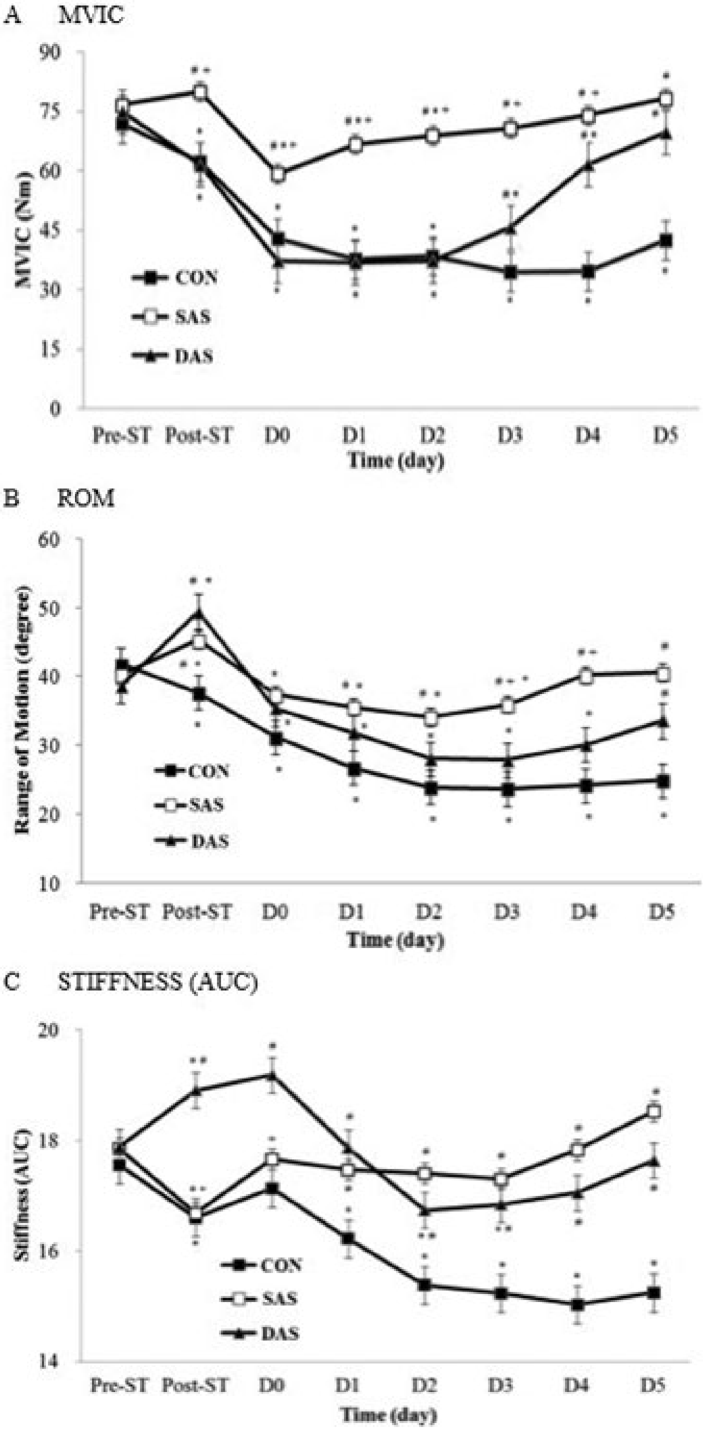

Figure 4 — Changes (mean ± SEM) in (A) maximal voluntary isometric contractions (MVIC), (B) ROM, and (C) muscle stiffness prestretching (pre-ST), poststretching (post-ST), after maximal eccentric exercise (post-ECC) (D0), and D1 to D5 post-ECC for the control (CON), static-active-stretching (SAS), and dynamic-active-stretching (DAS) groups. *Significant difference from the pre-ST value. #Significant difference from the CON group. +Significant difference from the DAS group.

As shown in Figure 4(B), a significant 2-way interaction (time × intervention) was also noted ($P < .001$). The CON group showed a significant decrease in ROM relative to the SAS (D1–D5) and DAS (D5) groups after eccentric exercise. The SAS group showed significantly greater ROM than the DAS group during the D3-to-D4 period after eccentric exercise.

For muscle stiffness (AUC), a significant 2-way interaction (time × intervention) was noted ($P < .001$). After eccentric exercise (D0), the increase in AUC was significantly larger in the DAS group than in the SAS and CON groups. The AUC of the CON group decreased significantly relative to those of the SAS and DAS groups during the D1-to-D5 period after eccentric exercise (Figure 4[C]).

For muscle soreness, a significant 2-way interaction (time × intervention) was noted ($P < .001$). Soreness was significantly smaller in the SAS and DAS groups than in the CON group during the D3-to-D5 period after eccentric exercise. In addition, soreness was significantly less in the SAS group than in the DAS group after eccentric exercise at D2 after eccentric exercise (Figure 5[A]).

For plasma CK activity and Mb concentration, a significant 2-way interaction (time × intervention) was noted ($P < .001$). All groups showed a significant increase in CK and Mb after eccentric exercise. Increases in CK and Mb were smaller in the DAS and SAS groups than in the CON group. In addition, the CK and Mb of the SAS group were significantly lower than those of the DAS group at D3 to D5 after eccentric exercise (Figure 5[B] and [C]).

Discussion

The current study is the first to investigate the effect of decreased muscle damage induced by maximal eccentric exercise between jogging plus SAS or DAS stretching exercises versus jogging only (CON). The 3 groups had significant changes in the outcomes of interest, such as HR, ROM, muscle stiffness, and MVIC. These results partially support the first hypothesis, that both types of active stretching would significantly increase hamstring flexibility (SLR ROM) relative to the CON group. For MVIC, however, change in the SAS group (3.4 ± 1.9 Nm) was significantly better than those in the CON (–9.6 ± 2.4 Nm) and DAS (–13.4 ± 2.1 Nm) groups. Furthermore, increases (SAS 12%, DAS 27%) in hamstring ROM after active stretching were observed without corresponding improvements in muscle stiffness. These findings are in agreement with the findings of previous studies that stretching (passive SS or SS and proprioceptive neuromuscular facilitation) improves hamstring ROM but does not improve muscle compliance (or muscle stiffness).[6,15,18] Because there was no significant difference in CT between DAS and SAS exercises, we propose that the effect of stretching on viscoelastic properties of musculotendinous units may be similar in the 2 protocols. Therefore, the gain in hamstring flexibility (SLR ROM) may be due to an increased tolerance or elicited elevated sensory and pain threshold for stretching force, as proposed by Magnusson.[18,19]

Muscle strength after stretching can be affected by muscle flexibility, muscle stiffness, passive resistive torque,[20] and/or intensity of stretching.[8] Originally, we proposed that DAS might have a positive effect on muscle contraction. The results, however, contradicted the hypothesis. Similarly, another study suggested that dynamic stretching reduced maximal isokinetic (60°/s and 180°/s) concentric and

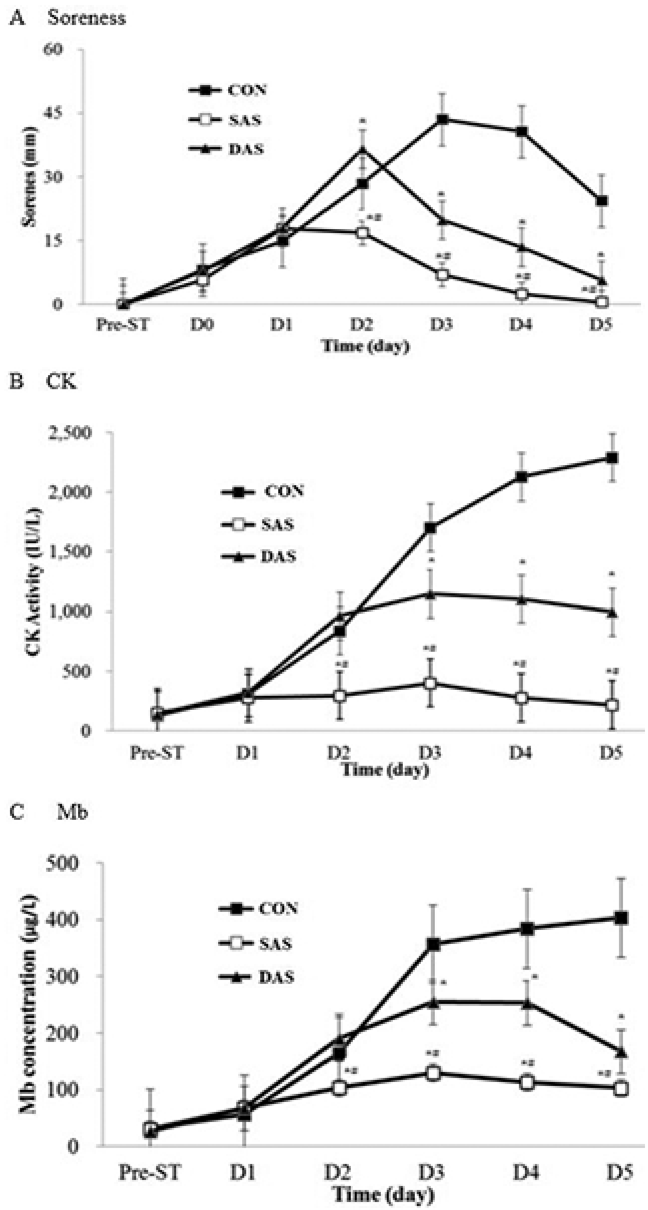

Figure 5 — Changes (mean ± SEM) in (A) soreness, (B) plasma creatine kinase (CK) activity, and (C) myoglobin (Mb) concentration prestretching (pre-ST), poststretching (post-ST), after maximal eccentric exercise (post-ECC) (D0), and D1 to D5 post-ECC for the control (CON), static-active-stretching (SAS), and dynamic-active-stretching (DAS) groups. *Significant difference from the CON group. #Significant difference from the DAS group.

eccentric strength in the hamstrings.[21] However, the mechanism by which dynamic-stretching technique impairs hamstring muscle strength remains unclear. It appears that increasing muscle flexibility by stretching can reduce force production. This may be due to decreased cross-bridge formation, which subsequently reduces the muscle's ability to efficiently generate activity.[20] The stretching can decrease musculotendinous-unit stiffness and lead to less-efficient force transfer from the muscle to the tendon.[20] It has been reported that a stiffer musculotendinous unit is significantly related to maximal isometric performance.[22] This mechanism seems to apply to our SAS protocol in that the muscles become stiffer after stretching, thus resulting in maintained muscle strength. Conversely, increased AUC (less stiffness) and reduced hamstring MVIC were found in the DAS protocol.

In addition, the intensity of stretching and sample (athletic or not recreationally active) may affect the muscle contraction after stretching. HR was monitored to reflect the intensity of stretching in previous studies.[8,23] The increased HR responses (31.3–130% for soccer or college-games athletes) after stretching were consistent with improved muscle contraction or leg-muscle power.[7,23] In our results, increases in HR recorded for the CON group may reflect their condition after 5 minutes of jogging warm-up (treadmill at 6.4 km/h with 1% grade). In addition, increased HR in the SAS group (61.4%) corresponded to the increase in muscle contraction. However, the increased HR of DAS (120.3%) demonstrated a decrease in muscle contraction. For our non–recreationally active sample, we propose that the intensity of DAS was excessive (increased HR 120.3%) and could induce acute fatigue, which in turn could impair muscle contraction. Previous studies have suggested that dynamic warm-up and stretching can provide acute positive effects on muscle performance by postactivation potentiation caused by conditioning contractile history.[24] Our results suggest that postactivation potentiation can be manipulated by type and/or intensity of stretching protocols, as well as by sample. Furthermore, as compared with the SAS protocol, the DAS protocol, featuring repetitive contraction of muscles in a short time, might result in muscle fatigue. The SAS protocol, in which participants are instructed to assume a forward lunge position (performing closed kinetic chains with weight bearing) can activate the electromyographic activities of the gluteus maximus and biceps femoris and thus improve performance.[25] Our findings suggest that the SAS technique, as opposed to the DAS technique, seems to offset the reduction in muscle flexibility and may be an effective technique for enhancing hamstring muscle performance.

Evidence supporting increases in muscle flexibility as a result of stretching and significantly correlated with reduced muscle damage is limited.[3,4] Notably, the current study is the first to show that SAS and DAS stretching can attenuate muscle damage. Furthermore, SAS stretching not only offsets the reduction in muscle stiffness (decreasing the AUC value) but also maintains hamstring muscle strength and prevents potential muscle damage (less increased muscle soreness, lower CK activity, and lower Mb concentration). Thus, our results support the second hypothesis; both DAS and SAS were more effective than the CON condition in attenuating eccentric-exercise-induced muscle damage. Similarly, previous studies have reported that significant increases in hamstring flexibility are significantly correlated with the magnitude of decreases in the markers of muscle damage.[3] We suggest that dynamic stretching can decrease musculotendinous-unit stiffness and diminish the imposed load across the muscle–tendon junction in the rapid eccentric-contraction phase. Previous studies also found that active warm-up immediately preceding eccentric exercise may increase muscle damage.[26] Furthermore, muscle soreness, plasma CK activity, and Mb concentration were significantly greater in the DAS group than in the SAS and CON groups 48 hours after eccentric exercise. These results indicate that DAS may induce more muscle damage than SAS.

Practical Implications

Both types of active stretching exercises can increase hamstring ROM and attenuate muscle damage induced by maximal eccentric exercise.

DAS may induce acute fatigue and impair muscle performance in an untrained population.

SAS is recommended over DAS as a stretching protocol because of its positive effects on strength, hamstring ROM, and damage markers.

Conclusions

Both SAS and DAS stretching exercises can increase ROM and attenuate muscle damage induced by maximal eccentric exercise. Although a stretching-induced force deficit is common, muscle strength was not impaired immediately after SAS in our study. Given the positive effects of SAS in terms of strength, hamstring ROM, and damage markers, SAS is recommended over DAS as a stretching protocol.

Acknowledgments

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