An Acute Bout of Static Stretching: Effects on Force and Jumping Performance

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ABSTRACT

POWER, K., D. BEHM, F. CAHILL, M. CARROLL, and W. YOUNG. An Acute Bout of Static Stretching: Effects on Force and Jumping Performance. *Med. Sci. Sports Exerc.*, Vol. 36, No. 8, pp. 1389–1396, 2004. **Introduction/Purpose:** The objectives of this study were to examine whether a static stretching (SS) routine decreased isometric force, muscle activation, and jump power while improving range of motion (ROM). Second, the study attempted to compare the duration of the dependent variable changes with the duration of the change in ROM. **Methods:** Twelve participants were tested pre- and post- (POST, 30, 60, 90, and 120 min) SS of the quadriceps and plantar flexors (PF) or a similar period of no stretch (control). Measurements during isometric contractions included maximal voluntary force (MVC), evoked contractile properties (peak twitch and tetanus), surface integrated electromyographic (iEMG) activity of the agonist and antagonistic muscle groups, and muscle inactivation as measured by the interpolated twitch technique (ITT). Vertical jump (VJ) measurements included unilateral concentric-only (no countermovement) jump height as well as drop jump height and contact time. ROM associated with seated hip flexion, prone hip extension, and plantar flexion-dorsiflexion was also recorded. **Results:** After SS, there were significant overall 9.5% and 5.4% decrements in the torque or force of the quadriceps for MVC and ITT, respectively. Force remained significantly decreased for 120 min (10.4%), paralleling significant percentage increases (6%) in sit and reach ROM (120 min). After SS, there were no significant changes in jump performance or PF measures. **Conclusion:** The parallel duration of changes in ROM and quadriceps isometric force might suggest an association between stretch-induced changes in muscle compliance and isometric force output. **Key Words:** ACTIVATION, PLANTAR FLEXORS, POWER, QUADRICEPS, RANGE OF MOTION

It is generally accepted and recommended to perform stretching routines after a light aerobic activity as part of a preexercise warm-up (33). Stretching has been demonstrated as an effective means to increase range of motion (ROM) about the joint (3) and is commonly utilized by athletes to decrease muscle soreness (14), reduce (24) or prevent (26) the risk of injury resulting from tight musculature, and rehabilitation after injury (17). In recent years, however, the proposed benefits of stretching before exercise have undergone considerable scrutiny. Although there have been reports of injury risk reduction due to stretching (13), it was concluded in a review by Shrier (25) that stretching is unlikely to prevent injury. In addition, recent studies have shown that various stretching routines are sufficient to induce strength (2,4,12,18,19,23) and power deficits (31) ranging from approximately 5 to 30% (33) for up to 1 h poststretch (12) and have been suggested to be joint-angle (20) and velocity specific (21).

Recommendations to abandon preexercise static stretching seem premature, however, in light of the fact that the majority of stretching protocols utilized to investigate force decrements were prolonged and not representative of commonly employed stretching routines. For example, Behm et al. (4) used five different static stretches (SS) for the quadriceps over a 20-min time frame whereas Fowles et al. (12) stretched the plantar flexors (PF) for a total of 30 min. Furthermore, not all sporting activities are negatively impacted by prior stretching. Wilson and colleagues (30) concluded that a more compliant series elastic component increased the ability to store and release elastic energy during the rebound bench press lift. Although static stretching may be an efficient method for increasing ROM (27), the aforementioned research (2,4,12,18,19,23,31,33) highlights potential risks to performance. Thus, if preexercise static stretching were deemed necessary for sporting activities involving maximal force and power, it would seem benefi-

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cial to determine the duration of possible stretch-induced decrements. Impairment timelines could then be employed as a means to formulate recommendations as to when pre-exercise stretching should be performed. For example, if the negative effects of stretching have subsided within 60 min of stretching but ROM remains increased for 120 min, then one could speculate that the athlete could stretch 60 min preexercise without any adverse effects.

Consequently, the objective of this study was twofold in nature: 1) to determine whether a more moderate volume of static stretching was still sufficient to decrease isometric force and power output and 2) to establish a force and power output deficit timeline if decrements were observed. Based on the existing literature, it was hypothesized that an acute bout of SS would adversely affect isometric force and jump performance while increasing ROM.

METHODOLOGY

Subjects

Twelve male volunteers (20–44 yr, 181.6 cm ± 14.8, 87.3 kg ± 15.2) were recruited from the university population. Participants were verbally informed of the procedures, and read and signed a consent form and a physical activity readiness questionnaire (PAR-Q) before participation. The Memorial University of Newfoundland Human Investigation Committee approved the study.

General Study Design

Participants acted as their own control group. The study consisted of five testing days. Day 1 was used for participant familiarization with the testing procedures (i.e., vertical jump techniques, isometric muscle contractions, electrical stimulus). During the familiarization period, subjects performed a minimum of three trials each for all tests (i.e., maximum voluntary contraction, concentric-only jump, drop jump, stretching). The order of testing on testing days 2–5 was randomized to test the plantar flexors (PF) or the quadriceps muscle group (i.e., day 1: control: no stretching with testing of quadriceps; day 2: experimental: stretching with testing of PF; day 3: experimental: stretching with testing of quadriceps; and day 4: control: no stretching with testing of PF). Quadriceps and PF testing was conducted on separate days because the number of voluntary and evoked contractions involved and the two separate devices needed for testing the two muscle groups, in addition to the jump measures, would have resulted in an excessively prolonged testing session. The testing days were interspersed with a minimum of 24-h rest. For a schematic representation of the methodology refer to Figure 1.

Warm-up

Participants performed a 5 min submaximal warm-up on a cycle ergometer. The participants were instructed to cycle at 70 rpm with a resistance of 1 kp to increase muscle temperature, although this was not directly measured. All participants developed a light sweating response, indicating a small increase in core temperature.

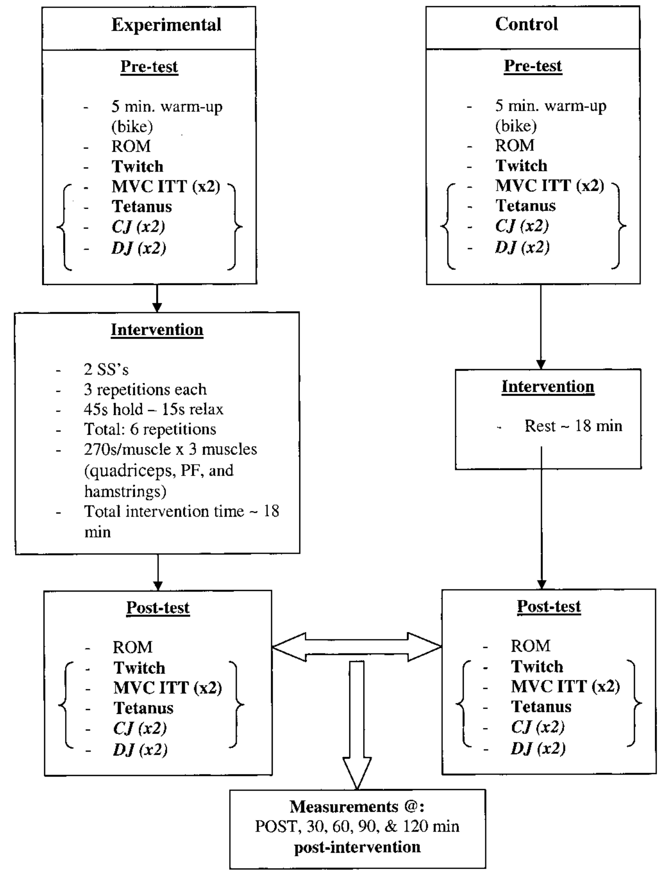

FIGURE 1—Methodological overview: a schematic representation of the methodology employed. The force and power measurements are indicated via bold and italic lettering respectively. Randomized variables are indicated by brackets.

Intervention

Three muscle groups (quadriceps, hamstrings, and PF) of the dominant leg (leg used to kick a soccer ball) received two successive SS each consisting of three repetitions each. Based on previous research that has recommended 30 s or greater duration of stretching (3,9), each stretch was held for 45 s followed by a 15-s relaxation period for a total stretching period of 270 s per muscle. The order in which the muscle groups were stretched was randomized. All stretches were held at the position to the onset of pain. This position was described to the participants as stretching the muscle to the greatest voluntary length beyond which the participant felt injury might occur. Stretches included the standing straight knee and standing bent knee (PF), the modified hurdler and supine hip flexion (hamstrings), and the prone buttocks kick and kneeling buttocks kick (quadriceps). The tester assisted with the supine hip flexion, prone buttocks kick, and kneeling buttocks kick.

Stretches

Standing straight knee. The participant leaned against a wall bending the front leg at the knee (90°) and keeping the other leg fully extended behind the body. The heel of the back leg remained in contact with the floor. The participant would then dorsiflex the ankle of the extended back leg until reaching the point of pain.

Standing bent knee. Similar to standing straight knee except the knee of the leg to be stretched was placed in a bent position.

Modified hurdler. The participant started in a seated position on a mat. The nonstretched leg was externally rotated at the hip and flexed at the knee with the sole of the foot in contact with the inside of the opposite thigh. With the leg to be stretched fully extended, the participant then leaned forward (hip flexion) to stretch the lower back and hamstrings of the extended leg.

Supine hip flexion. With the participant lying supine on the floor, the tester held the leg to be stretched by the ankle and knee (to ensure full extension) and pushed the leg back toward the participant's upper torso (hip flexion). The nonstretched leg was fully extended and in contact with the floor and supported in that position by the tester.

Prone buttocks kick. With the participant lying prone on the floor, the nonstretched leg was fully extended while the leg to be stretched was flexed at the knee. The tester held the leg to be stretched by the ankle and pushed the ankle back toward the buttocks (actively increased knee flexion).

Kneeling buttocks kick. With the torso upright, participants kneeled on a mat with one hip flexed and one hip extended and both knees flexed at 90°. The leg to be stretched was held by the ankle and pushed toward the buttocks (actively increased knee flexion).

Experimental Setup

Knee extensors. Participants were seated on a bench with their hips and knees flexed at 90°. Restraints were placed over the quadriceps, across the hips, and around the chest to ensure consistency of joint angles (90° at hip and knee). The lower limb was inserted into a padded strap at the ankle and attached by a high tension wire to a Wheatstone bridge configuration strain gauge (Omega Engineering Inc. LCCA 250, Don Mills, ON). Bipolar surface stimulating electrodes were secured over the inguinal space, superficial to the femoral nerve as well as the distal portion of the quadriceps immediately superior to the patella. Surface electromyography (EMG) recording electrodes (MediTrace Pellet Ag/AgCl electrodes, Graphic Controls Ltd., Buffalo, NY) were placed collar to collar (dimensions 3 × 2 cm) over the mid-belly of the vastus lateralis and long head of the biceps femoris. Ground electrodes were secured on the tibia and fibular head.

Plantar flexors. Participants were seated in a straight back chair with hips and knees at 90°. Contractions were performed or elicited with their leg secured in a modified boot apparatus (12) with their ankles at 10° of dorsiflexion; the optimal angle for plantar flexion force production (12). Bipolar surface stimulating electrodes were secured over the popliteal space and immediately superior to the gastrocnemius-soleus intersection. Surface EMG recording electrodes (same as previous) were placed over the soleus at the gastrocnemius-soleus intersection and over the mid-belly of the tibialis anterior. Ground electrodes were secured on the tibial shaft.

Electrode measurement and preparation. Thorough skin preparation for all recording electrodes included removal of body hair and dead epithelial cells with a razor and abrasive (sand) paper around the designated areas, respectively. This preparation was followed by cleansing of the designated areas with an isopropyl alcohol swab. EMG activity was amplified (× 1000), filtered (10–1000 Hz), rectified (Biopac Systems Inc., Holliston, MA), monitored, and stored on computer (HP Pavilion N5310). The integrated electromyographic (iEMG) activity was measured over a 1-s duration beginning at 250 ms after the first stimulus during the interpolated twitch technique (ITT).

Stimulating electrodes, 4–5 cm in width, were constructed in the laboratory from aluminum foil, and paper coated with conduction gel (Signa Creme, Parker Laboratories, Fairfield NJ) and immersed in a saline solution. The electrode length was sufficient to wrap the width of the muscle belly. The electrodes were placed in approximately the same position for each participant.

Force measurement. All voluntary and evoked torques were detected by strain gauges, amplified (Biopac Systems Inc., DA 100: analog-digital converter MP100WSW, Holliston, MA) and monitored on a computer (HP Pavilion N5310). Data were stored at a sampling rate of 2000 Hz and analyzed with a commercially designed software program (AcqKnowledge III, Biopac Systems Inc.).

Evoked contractile properties. Peak twitch torques were evoked with electrodes connected to a high-voltage stimulator (Digitimer Stimulator Model DS7H+, Hertfordshire, UK). The amperage (10 mA-1A) and duration (50 μs) of a 100–150 V square wave pulse was progressively increased until a maximum twitch torque was achieved. The average of three trials was used to measure twitch amplitude (PT). Tetanic stimulation (100 Hz) was administered at the same stimulus intensity as the twitch for a 300-ms duration.

Interpolated twitch technique (ITT). The ITT was administered, with two evoked doublets superimposed at 1.5-s intervals on two maximal voluntary contractions (MVC) to estimate an average superimposed signal (5) (Fig. 2). Furthermore, a potentiated doublet was recorded 1.5 s after the voluntary contractions. Superimposed doublets rather than twitches were utilized to increase the signal-noise ratio. An IT-doublet ratio was calculated comparing the amplitudes of the superimposed stimulation with the postcontraction stimulation to estimate the extent of inactivation during a voluntary contraction (interpolated doublet amplitude/potentiated doublet amplitude × 100 = percentage of muscle inactivation). A ratio estimating muscle inactivation rather than activation was calculated, because the superimposed or interpolated force evoked upon the voluntary contraction activates those muscle fibers "not activated" or left "inactivated" by the voluntary command. Rest periods of 2 min were provided between contractions. A minimum of two MVC using the ITT were performed dur-

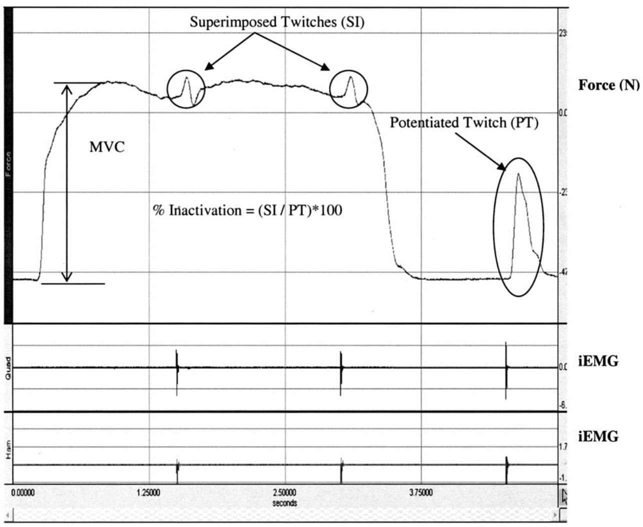

FIGURE 2—Interpolated twitch technique: an interpolated doublet ratio was used to estimate the extent of muscle inactivation during a MVC. % Inactivation was calculated by dividing the superimposed stimuli (SI) during the MVC by the postcontraction potentiated twitch (PT). MVC was calculated by a peak-to-peak measurement (the difference between baseline and the highest point of voluntary force recorded) (5).

ing the pretest unless there was greater than a 5% difference in force that resulted in a third MVC with ITT. Only one MVC with the ITT was performed during each posttest to reduce the effects of fatigue.

Vertical jumping tests. All jumps were performed unilaterally with the dominant leg on a contact mat (Innervations, Muncie, IN) and analyzed using a commercially available software program (Kinematics Measurement Systems, Innervations). Measurement variable for the concentric-only jump (CJ) was jump height, whereas the drop jump (DJ) variables included contact time and jump height. A minimum of two CJ and DJ were performed during the pretest unless there was greater than a 5% difference in jump height, which resulted in a third jump. Only two CJ and DJ each were performed during each posttest to reduce the effects of fatigue. A countermovement jump was contemplated and trial tested, but the consistency or reliability of

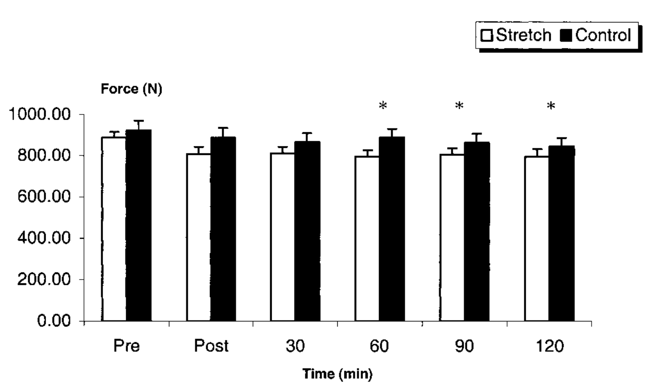

FIGURE 3—Effect of static stretching on quadriceps MVC: columns represent the maximal voluntary contractions of the dominant quadriceps for the stretch and control conditions. *Asterisks* indicate significant differences ($P < 0.05$) between stretch and control conditions. *Vertical bars* represent the SE.

the ROM was difficult to maintain. A comparison of CJ and DJ provided a comparison of vertical jumps emphasizing impulse versus the stretch-shortening cycle, respectively.

Concentric jump (CJ). The participants initially stood on the contact mat with knee flexed to 90°. The participant then held the position for a 2-s period at which time they were instructed to jump as high and fast as possible. Participants left the mat with the knee and ankle fully extended and landed in a similarly extended position to ensure that accurate flight time was recorded. The CJ eliminated any active prestretch of the musculature and thus only utilized a concentric contraction. The nondominant leg was flexed at the knee and maintained in a neutral position throughout the jump to mitigate any potential momentum transfer.

Drop jump (DJ). The participants performed a DJ from a 30-cm-high platform. Based on previous studies (31,33), this jump distance was felt to be sufficiently high to stress the stretch-shortening cycle and yet allow the participants to emphasize a short transition or contact time. The participants were instructed to place their hands on the hips and step off the platform with the leading leg straight to avoid any initial upward propulsion ensuring a drop height of 30 cm. They were instructed to jump for maximal height and minimum ground contact time. The participants were again instructed to leave the mat with knees and ankles fully extended and to land in a similarly extended position to ensure the validity of the test as the software assumes flight time up and down are equal.

Range of motion (ROM). ROM of the hip flexors, hip extensors, and plantar flexors of the dominant leg were measured. Hip extensor ROM was determined using the sit and reach test (7). Participants sat upright on the floor with their legs extended and feet dorsiflexed and placed against a measurement box. The individual then endeavored to reach forward with their arms extended toward or past their feet as far as possible. The distance in centimeters from or past the participant's feet was documented. Hip flexor ROM had the participants lying prone on the floor. With their anterior superior iliac spine in contact with the floor, the individual attempted to lift their leg as far as possible off the floor. The height of the knee was measured from the ground in cm (8). The hip flexor ROM test differed from the other ROM measures in that it was not gravity assisted and necessitated active contractions of the hip extensor musculature. While seated with legs above the floor hanging freely, plantar flexor ROM was measured with a goniometer from the position of full dorsiflexion to full plantar flexion (8). One lever of the goniometer was land marked on the proximal fibular head while the pivot was placed on the lateral malleolus. The other lever was positioned on the fifth metatarsal bone, and its position was used to determine the degrees of movement. Three trials of each stretch were performed pre- and posttests.

Statistical Analysis

Data were analyzed with a 2 (TREATMENT: experimental and control) × 6 (TIME: PRE, POST, 30, 60, 90, 120 min) ANOVA with repeated measures. Participants acted as their own controls. F-ratios were considered significant at $P < 0.05$. If significant interactions were present, a LSD *post hoc* analysis was conducted. Day-to-day reliability measures of the tests were conducted with a two way mixed (95% confidence intervals) intraclass correlation coefficient (SPSS software). Descriptive statistics include means and SE.

RESULTS

Isometric MVC. SS resulted in a significant ($P < 0.05$) 9.5% decrease in MVC force of the quadriceps (data collapsed over testing sessions). MVC force was significantly decreased for the 120-min testing duration (8.4%–10.4%), thus establishing a force deficit timeline (Fig. 3). MVC did not change significantly in the control condition or with the PF.

Inactivation (ITT). SS resulted in a significant overall 5.4% increase in the inactivation of the quadriceps ($P < 0.05$) (Fig. 4). There was no interaction effect between condition and time and thus a timeline associated with increased inactivation could not be established. Inactivation did not change significantly in the control condition or with the PF.

Electromyography. After the pretest, there was a nonsignificant decrease in quadriceps EMG activity of 15.1% and 16.5% immediately and 120 min poststretch, respectively. The PF, however, demonstrated a nonsignificant increase of 6.5% immediately poststretch with a 13.5% decrease at 120 min (nonsignificant).

Evoked contractile properties. In comparison with the pretest quadriceps peak twitch forces, there was a nonsignificant increase of 0.5% immediately poststretch and a nonsignificant decrease of 2.1% at 120 min posttest. Quadriceps tetanic forces decreased by 1.4% and 0.5% immediately and 120 min posttest, respectively (nonsignificant). PF twitch forces maintained an approximately 5% nonsignificant decrement throughout the poststretch testing period. Tetanic PF forces decreased 3.8% and 0.6% immediately and 120 min poststretch, respectively (nonsignificant).

Jump performances. In reference to the pretest, DJ contact times had nonsignificant decreases ranging from 2.6% to 10.1% over the 2 h poststretch testing period. Similarly, DJ heights decreased 5.1% to 6.5% over the posttesting period (nonsignificant). CJ height showed nonsignificant decreases between 2% and 5.4% over the testing period.

Range of motion (ROM). With data collapsed (stretching days combined) SS resulted in a significant increase in sit and reach ROM ($P < 0.05$) lasting 120 min (Fig. 5). When compared with the control condition, ROM increased by 10% (POST), 8% (30 min), 7% (60 min), 6% (90 min), and 6% (120 min) poststretch. Sit and reach ROM did not change significantly in the control condition. There were no significant differences in ROM during hip extension or plantar flexion between conditions.

Reliability. Intraclass correlation coefficient (reliability) measures ranged from 0.85–0.97 for voluntary isometric measures, 0.79–0.93 for vertical jump (VJ) measures, 0.72–0.75 for evoked contractile properties, and 0.85–0.98 for ROM measures.

DISCUSSION

The most significant findings in this study were that the SS routine resulted in 1) significant 9.5% and 5.4% average decrements in quadriceps MVC and ITT, respectively, with MVC force remaining significantly decreased at 120 min (10.4%), 2) significantly increased hip extensor ROM for 120 min (6%), and 3) no significant effect on jump performance variables. The decreased force and activation of various muscle groups after bouts of SS is consistent with other research (4,12). The fundamental difference between the aforementioned studies and the present study however is the duration of the applied SS. Whereas the total SS duration in the present study was 4.5 min per muscle group, Behm et al. (4) stretched the quadriceps for 15 min over a 20-min time frame whereas Fowles et al. (12) stretched the PF for a total of 30 min. Thus, even a more moderate duration of SS can result in quadriceps isometric force and activation decrements.

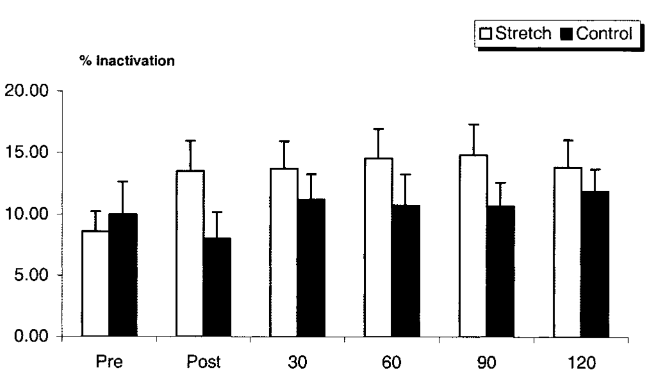

FIGURE 4—Effect of static stretching on quadriceps percent inactivation: *columns* represent the percent inactivation of the dominant quadriceps for the stretch and control conditions. *Vertical bars* represent the SE.

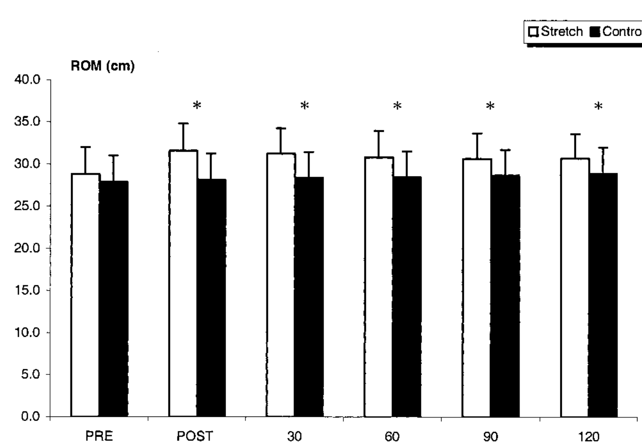

FIGURE 5—Effect of static stretching on hamstrings flexibility: *columns* represent range of motion (sit and reach test) of the hamstrings for the stretch and control conditions. *Asterisks* indicate significant differences ($P < 0.05$) between stretch and control conditions. *Vertical bars* represent the SE.

Force and activation. The decrease in MVC force was associated with a significant overall decrease in ITT, indicating the possibility of a neurological deficit. Whereas quadriceps EMG activity was also decreased with the stretching routine, the greater variability of the signal nullified any statistical significance. This neurological deficit was further supported by the absence of significant changes in PT or tetanus forces, which if decreased would indicate a peripheral impairment. However, the lack of a statistically significant interaction between changes in ITT and testing time would not permit a conclusive indication of the duration of the neurological deficit. It is unlikely that the neurological deficit was a significant contributor for the entire two-h testing period. Fowles et al. (12) reported a 20% decrease in force 5 min after stretching, which was accompanied by a significant 13% decrease in activation as measured by the ITT and a nonsignificant 15% decrease in EMG activity. In their discussion, they reviewed a number of factors such as autogenic inhibition and Type III (mechanoreceptor) and IV (nociceptor) afferents that could have contributed to the poststretch inactivation. However, as pointed out by Fowles et al. (12), Golgi tendon organ discharge rarely persists during maintained stretch and the inhibitory effects are transitory (1). They also commented that the discomfort and pressure would be present only during the stretch, with these inhibitory components absent 5–10 min after the stretching protocol, making it unlikely that inhibition induced by mechanoreceptors or nociceptors provided substantial inhibition during the testing period (12).

Some of the stretches used in the current study placed the knee in a position of maximal or near maximal flexion, which may have produced a significant amount of intra-articular knee pressure (15). Increases in intra-articular pressure have been reported to result in decreases in muscle activation (11). Whereas there was no measure of damage to the connective tissue in this study, the stress placed on the tissues around the knee may have caused a transient inhibitory effect on the quadriceps.

There was no significant force or activation decrement detected with the PF. In contrast to the tibia, the foot is composed of multiple bones that could help dissipate some of the torque effects. In addition, the SS employed for the PF were performed solely by the participant whereas the researcher assisted the stretches for the quadriceps. Thus, although the participants were told to stretch to the point of pain, the tester was unable to determine the relative tension placed on the PF.

If stretching can induce activation impairments (4,12), a more pliable muscle may experience less severe stress from the stretching protocol. Because the PF have been documented to possess a higher percentage of slow-twitch fibers than the quadriceps (16), differences between the PF and quadriceps may have also resulted from differing fiber compositions. As stated in a review by Smith (26), it has been suggested that slow-twitch fibers are more pliable than fast-twitch fibers. Furthermore, the bent knee testing position may not have placed the more fast-twitch predominant gastrocnemius (16) at an optimal length, obscuring any significant changes.

Avela et al. (2) investigated the effects of passive stretching of the triceps surae muscle on reflex sensitivity, providing a potential mechanism for decreased MVC force. After 1 h of stretching, there were significant decreases in MVC (23.2%), EMG (19.9%), stretch reflex peak-to-peak amplitude (84.8%), and the ratio of H-reflex to muscle compound action potential (M-wave) (43.8%). They suggested that the decrease in H-reflex amplitude resulted from a reduction in excitatory drive from the Ia afferents onto the α-MN, possibly due to decreased resting discharge of the muscle spindles via increased compliance of the MTU.

Behm et al. (4) demonstrated that SS of the quadriceps decreased twitch force by 11.7%, indicating increased MTU compliance. They concluded, however, that the lack of change in tetanic force coupled with the decrease in muscle activation levels suggested that the force decrease following stretching was more neurological than mechanical in nature. Similarly, Fowles et al. (12) reported a 10% decrease in PT after SS of the PF coupled with a decrease in ITT. They stated that even though full activation of the PF (ITT) was evident by 15 min of recovery, MVC remained decreased for up to 1 h poststretch. Thus, they suggested that the early phase of decreased MVC resulted from impaired activation and contractile force and by impaired contractile force for the force deficit duration (1 h). As ROM returns to prestretch values, it would be postulated that MTU compliance would also return to "normal," thus mitigating any decrease in force resulting from increased MTU compliance. This mechanism was unable to be determined in the present study however as the protocol lasted 120 min during which force decreases and increased ROM were still present. Kokkonen et al. (19) also concluded that force loss might have been a result of decreased MTU stiffness when they reported significant decreases in knee flexion (7.3%) and extension (8.1%) 1 repetition maximum forces after a SS protocol that was accompanied by significant increases in sit and reach ROM (16%).

It would be contentious to postulate that the prolonged isometric force impairments in the present study are solely related to neurological deficits. The stretch-induced isometric force decrement is more likely due to a combination of factors. Stretch-induced changes in muscle compliance or stiffness that endured over the 120-min testing period could have resulted in alterations to the force length relationship of the muscle also contributing to changes in force output.

Improved performance with a rigid MTU has been demonstrated to be favorable during isometric and concentric contractions (29). Wilson et al. (29) reported that MTU stiffness was significantly related to isometric and concentric performance ($r = 0.57$ and 0.78, respectively). They suggested that a stiffer MTU augments force production via an improved force-velocity and length-tension relationship. A stiffer MTU would be more effective during the initial transmission of force, thus increasing rate of force development.

Jumping performance. A seemingly perplexing result of the current study was that in light of decreased force and activation of the quadriceps following SS, VJ variables remained unaffected. Performances of power-related activities such as jumping are probably more reflective of changes in athletic performance than isometric MVC. Researchers have investigated the effects of dynamic stretching (DS) (22), SS (10,18,31), and proprioceptive neuromuscular facilitation (PNF) stretching (10,31) on jumping performance yielding mixed results. Church et al. (10) investigated varying warm-up procedures on VJ performance and demonstrated that PNF stretching significantly decreased VJ performance while SS had no effect. Correspondingly, a statistically nonsignificant decrease in VJ performance (3%) after SS was also found by Knudson et al. (18), who concluded that there was no difference in the biomechanics of the VJ performance that would suggest a more compliant MTU.

A recent study by Young and Behm (32) investigated the effects of submaximal running (4 min), SS (four stretches), and practice jumps (four squat jumps and four drop jumps) on jumping performance in an attempt to elucidate an optimal warm-up procedure. They concluded that SS produced a negative effect on CJ performance. It is also of interest that the SS method applied had a relatively low volume composed of two SS each for the PF and quadriceps, consisting of two repetitions of 30 s per each stretch. In support of these findings, Young and Elliott (31) demonstrated that SS significantly decreased DJ performance and suggested that the negative influence of SS might result from increased compliance of the MTU, which may be important for fast stretch shortening cycle (SSC) movements. Belli and Bosco (6) suggested that the work performed during SSC movements would be enhanced by a stiffer MTU during hopping movements. If MTU stiffness decreases after stretching, this may help explain the decreased jump height in other studies (10,31).

In opposition to jump performance benefits derived from MTU stiffness, Wilson et al. (29) concluded that increased compliance of the MTU was beneficial. They had participants perform flexibility training for 8 wk resulting in increased ROM and decreased series elastic component (SEC) stiffness. Participants showed increases in loads lifted with the rebound bench press (5.4%) and purely concentric bench press (4.5%), although only the former attained statistical significance. Corresponding with additional research (30), it was suggested that a more compliant SEC increased the ability to store and release elastic energy during the rebound bench press lift. The possibility of a positive association between force output and SEC compliance is further supported by Walshe and Wilson (28). They compared MTU stiffness and the ability to perform SSC DJ's from various heights. Results indicated that stiff participants were significantly disadvantaged at higher drop heights (DJ80 cm and DJ100 cm) than their more compliant counterparts. They postulated that the stiffer MTU would have a decreased ability to mitigate the high loads placed on it, thus stimulating increased inhibition during the DJ via the Golgi tendon organs. This inhibition would override the facilitation effect of the stretch reflex resulting from a bias toward a protective mechanism (28) when high levels of force are placed on the muscle. This finding may help explain the lack of difference in VJ variables evident in the present study. VJ testing is usually performed using a bilateral model (28,31,33). In the current study, however, participants stretched and performed VJ unilaterally. Thus, the DJ height of 30 cm in the current study performed unilaterally would exert significantly greater loads than bilaterally. Similar to the effect found with high drop jumps (28), a more compliant MTU might be more beneficial with unilateral jumps from 30 cm. Perhaps the use of a lower jump height or a bilateral jump which may benefit from a stiffer MTU may have resulted in deficits similar to the MVC.

Range of motion. In the present study, there was no significant increase in the ROM of the hip flexors although sit and reach ROM increased significantly immediately poststretch (10%) and remained increased for 120 min (6%). The lack of change in hip flexor ROM could be attributed to the fact that it involved active contraction of the hip extensors. If the SS routine caused a similar decrease in hip extensor force as it did in the hip flexors (quadriceps), it is possible that the hip extensors would be unable to fully support or raise the weight of the stretched leg to a position of maximal hip extension. Whereas the sit and reach measures the ROM of the hip extensors, similar studies have used the sit and reach as an indicator of increased ROM of muscle groups other than the hip extensors (19).

CONCLUSION

SS of the quadriceps resulted in a significant decrease in MVC force output paralleled by significantly increased sit and reach ROM (both lasting 120 min) whereas jumping performance was unaffected. Mechanisms responsible are hypothesized to be an interaction of neurological and mechanical factors.

These findings suggest that SS may impair isometric force production for up to 120 min. Thus, for activities involving maximal force output, it is suggested that SS such as the methods utilized in the current study be avoided at least 120 min preperformance. However, jumping activities involving higher reaction forces, which may benefit from a more compliant MTU may be able to successfully incorporate stretching before the activity.

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