Acute Effects of Static Stretching of Hamstring on Performance and Anterior Cruciate Ligament Injury Risk During Stop-Jump and Cutting Tasks in Female Athletes

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Abstract

Ruan, M, Zhang, Q, and Wu, X. Acute effects of static stretching of hamstring on performance and anterior cruciate ligament injury risk during stop-jump and cutting tasks in female athletes. *J Strength Cond Res* 31(5): 1241–1250, 2017—There is limited research investigating antagonist stretch. The purpose of this study was to evaluate the influence of static stretching of hamstrings (SSH) on performance and anterior cruciate ligament (ACL) injury risk during stop-jump and 180° cutting tasks. Twelve female college athletes (age 20.8 ± 0.7 years; height 1.61 ± 0.05 m; mass 54.25 ± 4.22 kg) participated in this study. Subjects performed stop-jump and 180° cutting tasks under 2 conditions: after warm-up with 4 × 30 seconds SSH or after warm-up without SSH. Three-dimensional kinematic and kinetic data as well as electromyography of biceps femoris, rectus femoris, vastus medialis, and gastrocnemius medialis were collected during testing. Static stretching of hamstrings significantly enhanced jump height by 5.1% ($p = 0.009$) but did not change the takeoff speed of cutting. No significant changes in peak knee adduction moment or peak anterior tibia shear force were observed with SSH regardless of the task. The peak lateral tibia shear force during cutting was significantly ($p = 0.036$) reduced with SSH. The co-contraction of hamstring and quadriceps during the preactivation (stop-jump: $p = 0.04$; cutting: $p = 0.05$) and downward phases (stop-jump: $p = 0.04$; cutting: $p = 0.05$) was significantly reduced after SSH regardless of the task. The results suggest that SSH enhanced the performance of stop-jump because of decreased co-contraction of hamstring and quadriceps but did not change the performance of cutting. In addition, SSH did not increase ACL injury risk during stop-jump and cutting tasks and even reduced medial-lateral knee loading during cutting.

Key Words pivot, ACL, co-contraction, 3D biomechanics

Introduction

Although proprioceptive neuromuscular facilitation, ballistic, dynamic, and static stretching are used commonly in sports, static stretching remains the most widely used because it is easy to implement. The main purpose of static stretching is to increase joint range of motion and its effectiveness has been proved by many studies (4,5). However, static stretching has been found to be detrimental to subsequent athletic performance that mainly relies on force and power production (29,38,55,56). Despite the inconsistent effects of static stretch–induced performance impairments reported in the literature, a meta-analytical review (49) showed a 6.5% and 3.9% decrease in isometric and dynamic strength, 1.9% decrease in power, and 2.0% decrease in explosive performance after performing static stretching protocols. The effects were not related to subjects' age, sex, or fitness level. Consequently, studies recommended removing static stretching as part of warm-ups for athletic activities with high demands of strength and power (19,56).

Static stretching protocols performed in the reviewed studies target only a single agonist muscle group (13,39,55) or combined agonist and antagonist muscle groups (40,56). Stretching the agonist muscles would decrease the resultant torque production because of less positive torque production associated with the decreased force of the agonist muscles. Conversely, stretching the antagonist would increase the resultant torque production because of less negative torques associated with the decreased force of the antagonist muscles. Sandberg et al. (47) confirmed that antagonist stretching (the hip flexors and dorsiflexors) resulted in greater jump height. They also found a significant

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improvement in knee extension torque during isokinetic knee extension after static stretching of the knee flexors (hamstring muscles). Therefore, it is reasonable to predict that a significant improvement in performance would occur during explosive movements after static stretching of hamstrings (SSH). However, the effect of antagonist stretching on torque production may be velocity specific (39,47) and joint-angle specific (37). Hence, with very limited studies on antagonist stretching, the acute effects of SSH on the performance of specific explosive movements remain unclear.

Besides the influence on performance, the decrease in hamstring strength induced by SSH could lower hamstring-to-quadriceps strength ratio as much as 9% (15), and consequently may increase the risk of anterior cruciate ligament (ACL) injury. A large percentage of ACL injuries occur during single limb maneuvers that involve deceleration and change of direction, such as jumping or cutting (11,43). Contracting the quadriceps during jumping or cutting can cause anterior tibial translation relative to the femur (44). The hamstrings may be able to stabilize the knee joint by imparting a posterior tibial drawer force that could counteract anterior tibial translation during jumping or cutting (26). In addition, the hamstrings could potentially protect the ACL against high abduction strain during high-impact landings by controlling the frontal plane knee motion (33). Girls with lower hamstring strength exhibited significantly reduced hip abduction moments, greater knee abduction alignment, and 76% greater normalized ACL loading during landing compared with girls with higher hamstring strength (54). Additionally, Weinhandl et al. (53) reported that fatigue-induced hamstring strength reduction significantly reduced knee flexion angles and increased ACL loading by 36% during sidestep cutting. However, Blackburn et al. (8) reported that greater hamstring stiffness rather than hamstring strength was associated with a more stable knee joint as evidenced by less anterior tibial translation, which suggests that insufficient hamstring stiffness may increase ACL injury risk. Besides reduced strength, SSH also increases hamstring extensibility and decreases passive stiffness (35). It is reasonable to predict that SSH may increase injury risks during jumping and cutting tasks; however, no studies have evaluated ACL injury risk after SSH.

Grouped as jumping or cutting tasks, drop-jump, stop-jump, sidestep cutting (45° cutting), and 180° cutting (pivoting) have been used to evaluate risk factors associated with ACL injury risk. However, a recent prospective cohort study showed that the drop-jump may not be a good screening test for ACL Injuries (30). Stop-jump requires a sudden deceleration before a vertical jump and replicates a real-life task such as a header in soccer or a running shot in basketball. Although sidestep cutting has been used extensively in studies and only few studies have used 180° cutting, Greig argued that 180° cutting provided a more realistic representation of a real game task (21) because maneuvers involving greater angles of direction change (90°–180°) occur more frequently during soccer games according to notational analysis in Premier League soccer (9). Compared with 45° cutting, 180° cutting also showed greater knee abduction motion and moments (14), indicating the task is closer to the injury threshold.

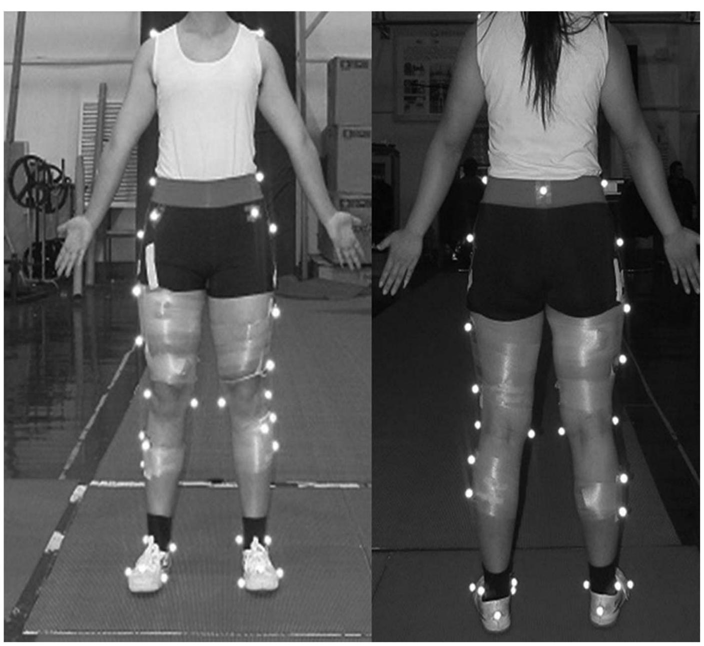

Figure 1. Marker placement.

Therefore, the purpose of this study was to investigate the influence of SSH on lower extremity biomechanics during stop-jump and 180° cutting tasks. It was hypothesized that performance of stop-jump and cutting after SSH would be enhanced as indicated by increased jump height and cutting speed. It was also hypothesized that ACL injury risk during stop-jump and 180° cutting after SSH would be increased as indicated by altered joint kinematics and joint kinetics.

Methods

Experimental Approach to the Problem

A within-subject experimental design was used to determine the effects of SSH. Subjects were asked to report to the laboratory on 3 different days, with 48 hours between the 2 testing days. Day 1 was used for participant familiarization with testing procedures. Day 2 and day 3 were used for data collection under the 2 experimental conditions for the stop-jump and cutting tasks: (1) warm-up with no stretch and (2) warm-up with SSH. The order of the 2 experimental conditions was random balanced across all subjects: 6 subjects performed condition 1 first, and the other 6 subjects performed condition 2 first.

Subjects

Twelve female college athletes (age 20.8 ± 0.7 years; height 1.61 ± 0.05 m; weight 54.25 ± 4.22 kg) who had received no less than 3 years of sports training were recruited to participate in this study. The subjects with a history of major lower limb injury were excluded. All subjects had experience doing stop-jump and cutting tasks as well as static stretching exercises, but none had knowledge about the purpose or hypotheses of this study. The Ethics Committee of the Shanghai University of Sport approved all study procedures, and subjects signed informed consent forms before they participated in the study. Subjects wore spandex shorts, spandex shirts, and the same type of athletic shoes during data collection.

Procedures

Before the data collection on testing days, wireless electromyographic (EMG) electrodes (Trigno wireless; Delsys, Boston, USA) were attached on biceps femoris (BF), rectus femoris (RF), vastus medialis (VM), and gastrocnemius medialis (GM) of subjects' dominant leg after the skin was shaved of hair and cleaned with alcohol (23). The dominant leg was determined based on the preferred jumping leg in a single-leg vertical jump. The rectangular (25 × 12 × 7 mm) electrodes were placed over the muscle belly aligned with muscle fiber orientation and were secured with strapping tape to minimize motion artifact. The distances between the electrodes were at least 3 cm to avoid any significant crosstalk (58).

Retroreflective markers (14 mm) were attached bilaterally on the subjects' acromioclavicular joints, iliac crest, anterior superior iliac spines, posterior superior iliac spines, greater trochanters, medial and lateral epicondyles of the knee, medial and lateral malleoli, first and fifth metatarsal heads,

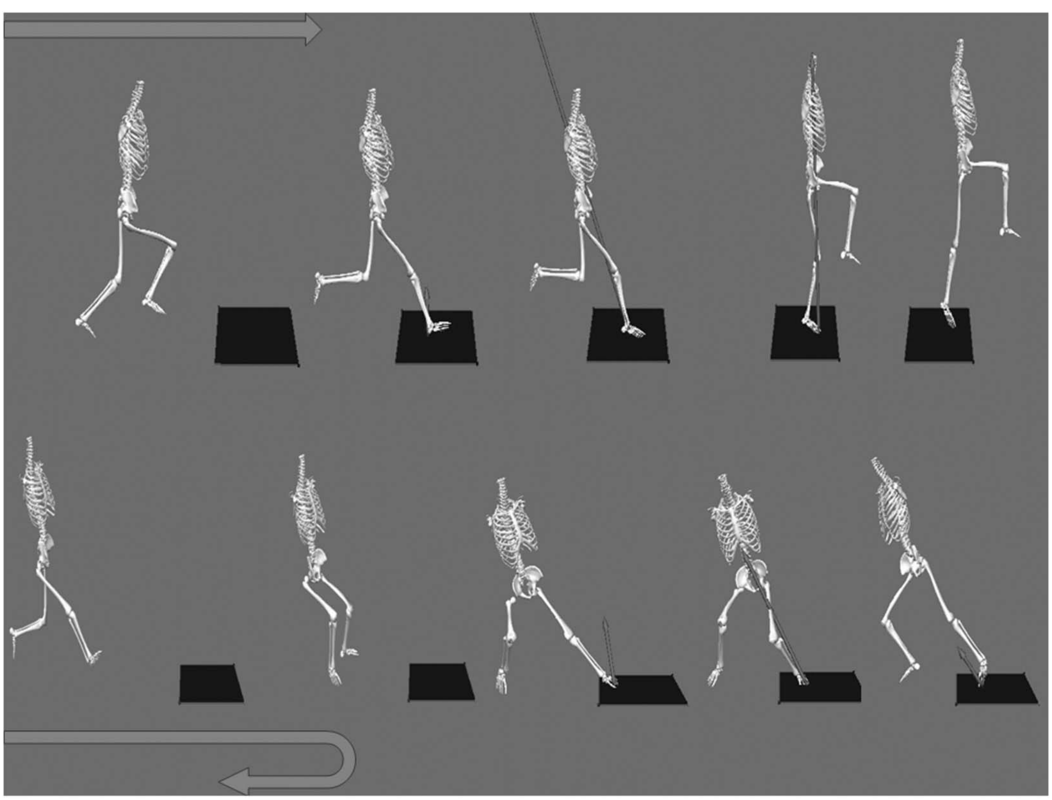

Figure 2. Stop-jump and 180° cutting tasks.

Table 1. Biomechanical variables related to performance.

Variables	Cutting: Nonstretch	Cutting: Stretch	Effect size (ES)	*p*	Stop-jump: Nonstretch	Stop-jump: Stretch	ES	*p*
Jump height (m)					0.41 ± 0.06	0.43 ± 0.05	0.43	0.009*
Takeoff speed ($m \cdot s^{-1}$)	2.53 ± 0.32	2.64 ± 0.38	0.31	0.486				
Approach speed ($m \cdot s^{-1}$)	3.54 ± 0.36	3.41 ± 0.41	0.34	0.470	4.57 ± 0.44	4.42 ± 0.34	0.38	0.566
Stance time (s)	0.52 ± 0.08	0.50 ± 0.07	0.27	0.431	0.20 ± 0.23	0.20 ± 0.17	0	0.108
Peak knee extension angular velocity ($deg \cdot s^{-1}$)	432.06 ± 108.80	428.78 ± 144.49	0.04	0.931	662.59 ± 82.95	697.42 ± 61.59	0.47	0.022*
Peak knee extension moment ($N \cdot m \cdot kg^{-1}$)	2.36 ± 0.52	2.33 ± 0.41	0.07.	0.803	3.66 ± 0.58	3.88 ± 0.69	0.35	0.189
Peak hip extension angular velocity ($deg \cdot s^{-1}$)	−298.20 ± 53.94	−307.17 ± 105.14	0.11	0.700	520.98 ± 84.89	502.86 ± 64.69	0.24	0.214
Peak hip extension moment ($N \cdot m \cdot kg^{-1}$)	2.70 ± 0.88	2.71 ± 1.03	0.01	0.998	7.32 ± 1.62	7.70 ± 2.12	0.21	0.144

*$p \leq 0.05$.

heels, and second toes. Additional rigid plates with 4 markers were attached to bilateral thighs and lower legs (Figure 1). Subjects performed a static calibration trial with all markers presented. The calibration markers, including those on the greater trochanters, medial and lateral epicondyles of the knee, and medial and lateral malleoli, were then removed before warm-up. After the calibration trial, subjects completed a 5-minute jog on a treadmill as a warm-up, followed by performing 3 countermovement vertical jumps, with the highest jump used for EMG normalization. After that, the stretch protocol was conducted, followed by stop-jump and 180° cutting testing. A vertical single-leg stop-jump task performed by the dominant leg included a 4-m approach run followed by one-footed landing and takeoff on a force platform (Figure 2). For the 180° cutting task, subjects started from 5 m away from the force platform and ran forward with maximum effort, planted their dominant foot on the force platform perpendicular to their approach running direction, and then accelerated off the force platform 180° to their initial running direction until past a cone 3 m away from the force platform (Figure 2). Subjects performed each task 3 successful trials.

Stretching Protocol

We used a passive static straight-leg raise to stretch the subjects' hamstrings. Subjects lay supine on a mat with the contralateral hip and knee stabilized in full extension. The investigator then pushed the stretching leg and took her into knee extension and hip flexion until the participant reported discomfort. All stretches were held for 30 seconds (4) and repeated 4 times with a 10-second rest between the stretches (29,39). The procedure was performed first on the dominant leg and then on the nondominant leg. In the no-stretch protocol, subjects rested for 5 minutes before they performed the cutting and stop-jump tasks.

Data Collection

The surface EMG signals were collected using wireless Ag electrodes with a parallel bar arrangement (contact area 1 × 10, 10 mm interelectrode distance) (Trigno wireless; Delsys) and preamplified close to the detection site (common-mode rejection ratio >80 dB, bandpass = 20–450 Hz). All acquired EMG data were recorded using Delsys EMGworks acquisition software at a sampling rate of 2000 Hz.

In addition to the EMG system, a 16-camera motion analysis system (200 Hz, Vicon Motion Analysis; Oxford, United Kingdom) and a force platform (1,000 Hz; Kistler Instruments, Winterthur, Switzerland) were used to simultaneously record the EMG signals, the 3D kinematics, and ground reaction forces (GRF), respectively, during the testing.

Data Reduction

The raw data were processed with a 3D biomechanical analysis suite, Visual 3D (C-Motion; Germantown, USA) to compute the 3D kinematic and kinetic variables, as well as

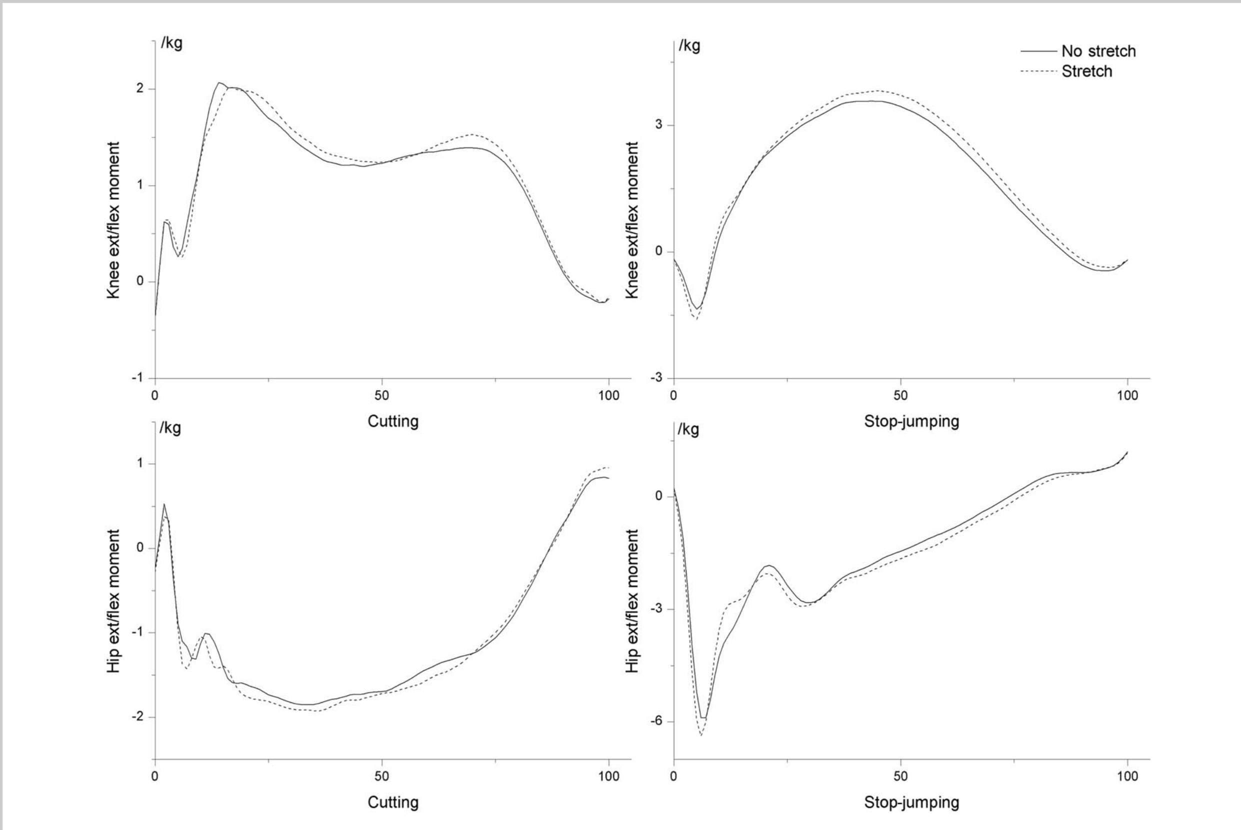

Figure 3. Group mean knee and hip joint moment in the sagittal plane during stop-jump and cutting tasks with and without static stretching of hamstrings.

the EMG variables. The data flow was intercepted from the point of initial contact (IC) to the point of toe-off from the force platform. The 3D marker coordinates and GRF signals were smoothed using a fourth-order Butterworth low-pass filter with cutoff frequencies of 10 and 100 Hz, respectively. The 3D angular kinematics was computed using a Cardan sequence (X-Y-Z), in which the order of rotation was flexion/extension, abduction/adduction (valgus/varus), and internal/external rotation. A right-hand rule was used to determine the polarity of the angular variables. An inverse dynamics approach was used to calculate the joint moments (57,60). The joint moment was normalized to the body mass, whereas the GRF, anterior tibial shear force, and lateral tibial shear force were normalized to the body weight. The time of peak posterior GRF (PPF) was identified as a critical time point for knee loading (32,60). Knee kinematic and kinetic variables at this critical time, including knee flexion angle (17,54), knee extension moment (17,54), knee abduction angle (54), knee adduction moment (54), the peak anterior tibial shear force (10), the peak lateral tibial shear force, hip adduction angle (27), and hip adduction moment (24), were used for evaluating the ACL injury risk. Jump height, which was used for evaluating stop-jump performance, was calculated by subtracting the vertical coordinates of the center of mass during the static trial from the maximum vertical coordinates of the center of mass during the stop-jump trials. The instantaneous horizontal velocity of the center of mass at the moment of foot contact during stop-jump and cutting was calculated to quantify approach speed (17). The instantaneous horizontal velocity of the center of mass at the moment of toe-off during cutting was calculated to quantify takeoff speed (17), which was used for evaluating 180° cutting performance.

Raw EMG signals were full-wave rectified and filtered using a moving root-mean-squared (RMS) filter with a window size of 50 ms. The maximum RMS values of the EMG signal of each of the 4 muscles in vertical jump testing were used to normalize the EMG of the respective muscle during the stop-jump and cutting trials. The vertical jump normalization was used because of its ability to provide reproducible reference EMG value for stretch-shortening cycle movements (3,20). The normalized EMG signals were then integrated into 3 time intervals: from 100 ms before foot contact for the preactivation phase (2), from foot contact to maximum knee flexion for the downward phase, and from maximum knee flexion to toe-off for

Table 2. Biomechanical variables related to anterior cruciate ligament injury risk.*

Variables	Cutting				Stop-jump			
	Nonstretch	Stretch	Effect size (ES)	p	Nonstretch	Stretch	ES	p
Knee flexion angle at initial contact (deg)	24.20 ± 7.13	21.52 ± 4.80	0.44	0.046†	22.82 ± 6.54	22.65 ± 6.44	0.03	0.912
Knee flexion angle at PPF (deg)	47.67 ± 9.31	47.13 ± 8.27	0.06	0.739	34.19 ± 7.76	37.98 ± 10.60	0.41	0.08
Knee abduction angle at PPF (deg)	−4.22 ± 5.69	−3.54 ± 7.31	0.08	0.642	0.85 ± 4.46	1.79 ± 5.28	0.20	0.393
Knee extension moment at PPF ($N \cdot m \cdot kg^{-1}$)	1.96 ± 0.74	1.94 ± 0.69	0.03	0.831	2.17 ± 1.11	2.34 ± 1.26	0.15	0.211
Knee adduction moment at PPF ($N \cdot m \cdot kg^{-1}$)	0.77 ± 0.45	0.70 ± 0.74	0.12	0.731	−0.99 ± 0.73	−1.29 ± 0.59	0.45	0.084
Hip adduction angle at PPF (deg)	28.24 ± 6.31	28.31 ± 7.96	0.01	0.967	8.81 ± 5.77	7.41 ± 4.20	0.28	0.358
Hip adduction moment at PPF ($N \cdot m \cdot kg^{-1}$)	1.30 ± 0.82	1.37 ± 1.39	0.06	0.816	−2.00 ± 0.71	−2.14 ± 0.69	0.20	0.575
Peak anterior tibial shear force (BW)	1.01 ± 0.14	1.00 ± 0.14	0.07	0.73	1.59 ± 0.21	1.62 ± 0.18	0.16	0.448
Peak lateral tibial shear force (BW)	0.51 ± 0.13	0.41 ± 0.19	0.60	0.036†	0.39 ± 0.18	0.35 ± 0.22	0.20	0.564
Peak posterior ground reaction force (BW)	1.57 ± 0.22	1.53 ± 0.21	0.19	0.519	1.64 ± 0.31	1.53 ± 0.23	0.41	0.131
Time to PPF (%)	14.69 ± 4.41	16.09 ± 5.30	0.31	0.0496†	20.65 ± 11.17	24.84 ± 10.76	0.38	0.079

*BW = body weight.
†$p \leq 0.05$.

the push-off phase. The integrated EMGs were further divided by the respective time intervals to obtain average EMG (aEMG) values. The co-contraction ratio of antagonist-agonist activation was calculated by dividing the average activation of the antagonist muscle (BF) by the average activation of the agonist muscle (RF and VM) (31,48).

Statistical Analyses

The results were expressed as mean ± *SD*. A paired-samples T-test was applied to compare each dependent variable between the 2 conditions of the independent variable of the study (with and without SSH). The jump height during stop-jump and the takeoff speed during cutting were primary dependent variables to test the hypothesis that performance of stop-jump and cutting after SSH would be enhanced. The approach speed, stance time, knee kinematics and kinetics, hip kinematics and kinetics, and GRF were additional dependent variables to provide details of the effect of SSH on the performance of stop-jump and cutting. The knee flexion angle at PPF, knee extension moment at PPF, knee abduction angle at PPF, knee adduction moment at PPF, and the peak anterior tibial shear force are primary dependent variables to evaluate the risk of ACL injury after SSH. The normalized EMG of RF, VM, BF, and GM as well as the co-contraction ratio of antagonist-agonist activation are dependent variables to evaluate the effect of SSH on muscle activation during stop-jump and cutting. Effect sizes (ES) were calculated using Cohen's d (12) for each dependent variable to further evaluate statistical differences, and the interpretation of the results was followed according to the scale provided by Cohen (12): <0.2 trivial effect; 0.2–0.5 small effect; 0.5–0.8 medium effect; and >0.8 large effect. Statistical significance was set as $p \leq 0.05$. Statistical analysis was performed using SPSS software (version 19.0; SPSS, Chicago, USA).

Results

The jump height during the stop-jump task was significantly greater (5.1%) with SSH compared with no SSH, and a greater peak knee extension velocity was also observed during the stop-jump with SSH. The takeoff speed during cutting did not change significantly after SSH (Table 1). No other performance-related variables changed significantly after SSH regardless of tasks. Patterns of extension moments at the knee and hip joints are shown in Figure 3.

No significant differences were found in any knee or hip joint parameters at PPF between conditions with and without SSH regardless of the task. Although no significant changes in the peak values of anterior tibial shear force and lateral tibial shear force were observed during stop-jump, a less peak lateral tibial shear force during cutting (Table 2) was observed after SSH. Additionally, the instant of the peak posterior GRF occurred significantly later during the cutting after SSH.

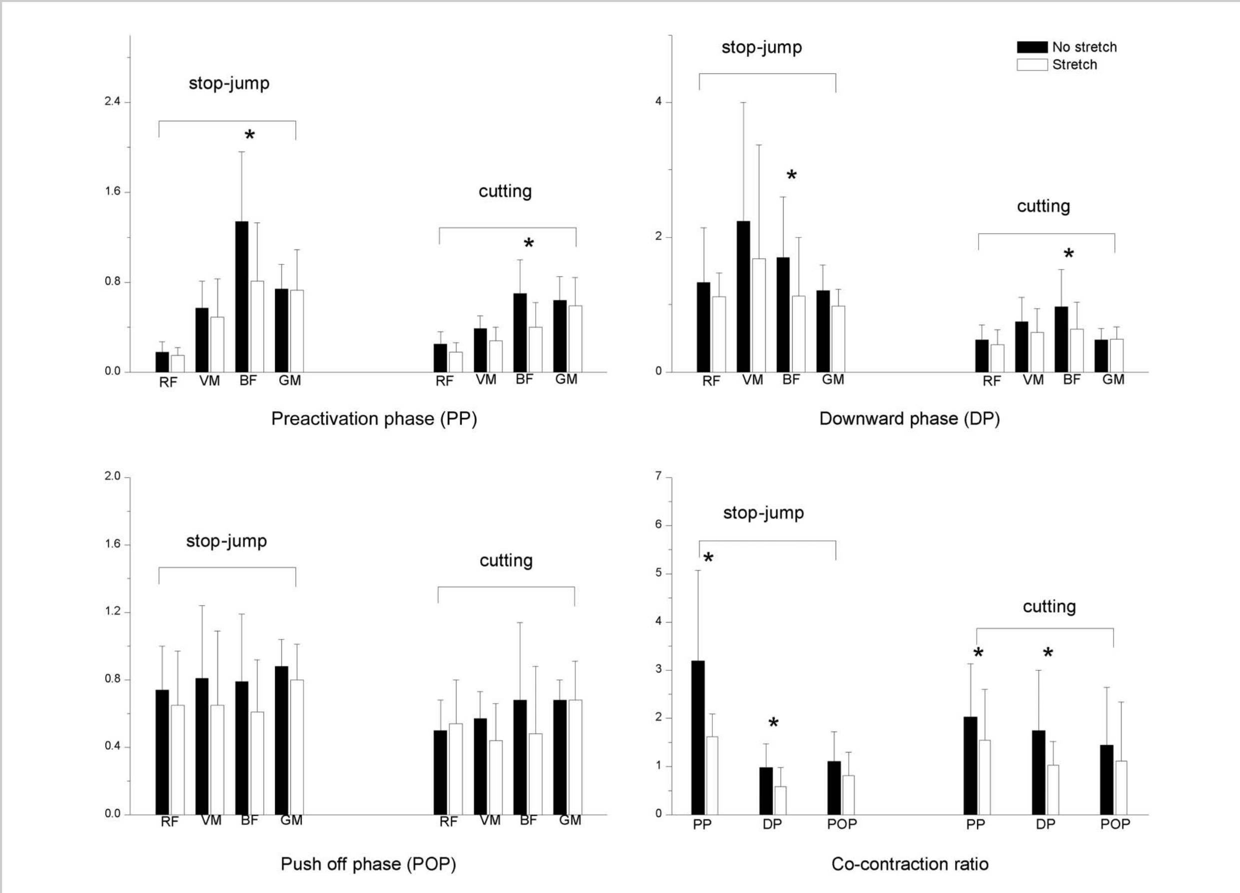

Figure 4. Normalized average electromyography and co-contraction ratio of the hamstring and quadriceps during stop-jump and cutting tasks with and without static stretching of hamstrings. Data represent mean + *SD*. *$p \leq 0.05$. RF = rectus femoris; VM = vastus medialis; BF = biceps femoris; GM = gastrocnemius medialis.

The aEMG of BF during the preactivation phase and the downward phase was significantly reduced after SSH for both tasks performed (stop-jump: $p = 0.04$, ES = 0.81; Cutting: $p = 0.032$, ES = 0.92) (Figure 4). No other examined muscles showed significant changes in the aEMG after SSH. Accordingly, the co-contraction of hamstring and quadriceps during the preactivation (stop-jump: $p = 0.04$, ES = 1.01; Cutting: $p = 0.05$, ES = 0.45) and the downward phases (stop-jump: $p = 0.04$, ES = 0.80; Cutting: $p = 0.05$, ES = 0.73) was significantly reduced after SSH regardless of the task (Figure 4).

Discussion

Although many studies have examined the effects of stretching on the performance of various activities including jumping and sprinting, the influence of stretching on joint kinematics and kinetics during these activities has not been reported. This is the first study to examine the influence of SSH on performance and injury risk based on joint kinematics and kinetics during stop-jump and 180° cutting tasks using the same subject group. Both stop-jump and 180° cutting are high-risk maneuvers associated with ACL injury, representing typical vertical and lateral movements. The results show SSH enhanced performance for stop-jump, but not for 180° cutting. Therefore, the results of this study partially support the hypothesis that performance of stop-jump and cutting after SSH would be enhanced. However, the lack of significantly changed anterior tibial shear force, knee abduction moment at PPF, knee extension moment at PPF, and knee flexion angle at PPF in both tasks indicated that no increased ACL loading had occurred after SSH. Thus, the second hypothesis, that ACL injury risk during stop-jump and 180° cutting after SSH would be increased, is not supported by this study.

The increased jump height during stop-jump after SSH was mainly attributed to significantly increased knee extension angular velocity, which is associated with a trend toward an increase in knee extension moment. This appears to support the hypothesis by Chappell et al. (10) in which reduced hamstring-to-quadriceps strength ratio would result in increased knee extension moment. Although we did not measure hamstring-to-quadriceps strength ratio directly, we observed that the muscle activation of the hamstring during the preactivation and downward phases, but not the push-off phase, was significantly reduced after stretching. Accordingly, the hamstring-to-quadriceps activation ratio, that is the co-contraction of hamstring and quadriceps, during the preactivation and downward phases was reduced. Ruan and Li (31) reported that for a typical stretch-shortening cycle movement, the increased activation of quadriceps during the preactivation phase would contribute to a greater stretch reflex, resulting in greater muscle activity of the quadriceps during the downward phase and a greater knee extension moment during the push-off phase, but muscle activity of the quadriceps during the push-off phase did not change. Although SSH did not increase the absolute preactivation level of the quadriceps, the relative increase in activation level of the quadriceps to hamstring during the preactivation and downward phases resulted in a greater knee extension moment (in trend but not statistically significant because of interindividual variability) and greater peak knee extension velocity. Reduced co-contraction has also been found during skill acquisition process, in which subjects progressed from a pattern of unnecessary muscular activity with greater co-contraction to an efficient movement strategy with reduced co-contraction (51). It would be interesting to examine whether static stretch of an antagonist muscle facilitates the skill acquisition process. However, the performance of cutting after stretching did not change significantly though similar changes in EMG occurred. This may be due to relatively less contribution from the quadriceps and more contribution from other no stretched muscles during the lateral movement.

Reduced co-contraction of the hamstring and quadriceps may be beneficial to athletic performance, but it may also increase ACL loading when knee flexion angles are greater than 22° (41). Weinhandl et al. (53) found that decreased hamstring strength relative to the quadriceps under a fatigue protocol increased ACL loading and potentially increased ACL injury risks. Increased knee abduction (valgus) angles and moments, decreased knee flexion angle, and increased knee extension moment, as well as increased anterior tibial shear force, have been shown to predict ACL injury risk (10,24). The results of this study showed that knee flexion angles at IC are greater than or almost equal to 22° and knee flexion angles at PPF are much greater than 22° regardless of tasks. However, no significant changes in kinematic or kinetic parameters associated with increased ACL injury risk were observed in this study. Although both fatigue and stretching protocol may reduce muscle strength, substantially different effects are induced by each. One difference might be the different magnitude of strength reduction. Although a significant decrement in strength of ~8% was reached at the beginning of the first set of movements in the fatigue protocol (42), pooled estimates for dynamic strength reduction induced by static stretching were only 3.9% (49). In addition to decreasing strength, fatigue affects movement coordination (50), increases muscle reaction times (22), reduces proprioceptive capabilities (25), and eventually may impair the ability to control body postures and promote abnormal leg joint motions (28,36). However, the influence of static stretch on body posture control and joint motions during high-intensity landing has not been investigated in the literature. This study shows that static stretching did not affect posture control and joint motions during high-impact dynamic movements, as evidenced by no significantly changed joint kinematics and joint kinetics at the critical time point. More surprisingly, the time to PPF was significantly delayed and lateral tibial shear force was significantly decreased during the cutting after SSH. Because most noncontact ACL injuries occur around 50 ms after the initial landing (27,45) and PPF is a critical factor affecting ACL loading (60), the delayed PPF may decrease ACL loading. The lateral tibial shear force may not be directly associated with ACL injury risk, but it has clinical implications for knee joint health because repeated medial-lateral stress may cause microdamage to the articular cartilage over time (46) and potentially result in osteoarthritis (34).

Additionally, the results of this study are not consistent with results reported by Wild et al. (54) in which girls with lower hamstring strength displayed greater knee abduction angle and greater ACL loading during landing from a leap compared with girls with higher hamstring strength. Athletes with less hamstring stiffness also displayed greater abduction moment, greater peak anterior tibial shear force, and less knee flexion angle at critical time points during landing than individuals with greater hamstring stiffness (7). This is also different than our results as stretching may decrease musculotendinous stiffness (13). One suggested explanation for this inconsistency is that chronic strength weakness or less stiffness may induce different compensations in landing mechanics over time compared with the acute effects of stretching (42).

The decrease in muscle activation of the hamstring observed in this study during the preactivation and downward phases after stretching is consistent with previous studies (16). There are several possible explanations for the decreased EMG: (a) a decrease in excitability of the α motoneuron due to inhibition generated by Golgi tendon organs (6); (b) a reduction in sensitivity of the muscle spindles (1); and (c) an increased inhibitory drive of the α motoneuron pool generated by joint receptors. However, other studies have also reported no changes in EMG poststretching (15,59). The lack of an inhibitory effect might be due to insufficient duration of the stretching applied (15), or differences in the pain threshold and flexibility levels among subjects (59). The difference in the EMG process protocol may also contribute to the inconsistency. In this study, EMG was divided by the preactivation phase, the downward phase, and the push-off phase, whereas other studies (18) used whole landing duration time as the time period.

This study has several limitations. Although EMG magnitude may provide some information about force production during explosive movements, no direct assessment of hamstring strength and stiffness was applied in this study. Using subjective perceptions of stretch intensity led to difficulty in ascertaining the effect of stretching on muscle activity. In addition, although ACL injury risks were evaluated using kinematic and kinetic parameters, ACL loading was not directly assessed. This study only recruited female athletes, who are less affected by stretching, and only acute effects of hamstring stretching have been evaluated. Thus, our findings should not be generalized to long-term effects or male athletes. Another limitation of this study was the relatively small sample size, which may have decreased the statistical power of the results. Certainly, further studies with a larger sample size and using objective stretch intensity are needed to determine mechanisms associated with muscle activity responding to stretching.

In summary, this study examined the effects of SSH on performance and injury risk during stop-jump and 180° cutting. No stretch-induced performance impairment was observed during 180° cutting, and jump height even increased after SSH. Although the co-contraction ratio of the hamstring and quadriceps was reduced after SSH regardless of the task, knee loading and injury risk did not increase during high-impact landings and lateral knee loading even decreased during 180° cutting.

Practical Applications

Antagonist stretching of the hamstrings significantly enhanced jumping performance, with an ES close to medium, and did not change landing mechanics or increase ACL injury risk. Consistent with the results of previous studies (47,52), these findings suggest that performing SSH immediately before an explosive jumping activity is favorable. Practitioners should incorporate SSH into the warm-up procedures before explosive movements. Reduced medial-lateral knee loading during cutting after SSH also suggests that SSH should be incorporated into the warm-up procedures before lateral movements.

Although this study showed that landing mechanics and knee loading did not change after SSH, caution has to be given to populations who have lower hamstring strength and stiffness because previous studies have identified those populations to be associated with greater risk of ACL injury, and SSH may further reduce hamstring strength and stiffness. Certainly, more research is necessary to evaluate the effects of SSH on landing mechanics for those populations.

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