Multiplanar Knee Laxity Increases during a 90-min Intermittent Exercise Protocol

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Abstract:

Purpose: This study aimed to examine changes in sagittal (AP_{LAX}), frontal (VV_{LAX}), and transverse (IER_{LAX}) plane knee laxity in men and women during an intermittent exercise protocol (IEP) simulating the intensity and duration of a soccer match.

Methods: Intercollegiate/club athletes (29 females and 30 males) were measured on AP_{LAX} (-90 to 130 N) before and after warm-up and every 15 min during and for 1 h after the IEP. VV_{LAX} (±10 N·m) and IER_{LAX} (±5 N·m) were measured before and after warm-up, at the end of each 45-min half, and at 30 min after exercise. Values were compared to a control (no exercise) condition.

Results: Compared to control condition, females increased AP_{LAX} and VV_{LAX} during the IEP, whereas males did not ($P < 0.037$). AP_{LAX} increased within 15 min of exercise (9.5 ± 2.1 mm), and peak values obtained at the end of the first (10.1 ± 2.0 mm) and second half (10.1 ± 2.1 mm) were 12% greater than before warm-up values (9.0 ± 1.8 mm). VV_{LAX} increased before warm-up (9.5° ± 3.4°) to the end of each half (both 10.4° ± 3.2°; 10% increase) and remained elevated 30 min after exercise (10.5° ± 2.9°). Both sexes increased IER_{LAX} from before warm-up (25.5° ± 6.1°) to all time points (after warm-up = 26.6° ± 6.0°, first half = 27.0° ± 6.6°, second half = 27.3° ± 6.5°, 30 min after exercise = 26.95° ± 5.7°; $P = 0.007$). Changes in AP_{LAX} (-0.10 to 5.9 mm), VV_{LAX} (-1.7° to 5.7°), and IER_{LAX} (-4.1° to 13.3°) during exercise varied considerably among individuals in both sexes, with a larger proportion of females experiencing substantial changes in AP_{LAX} and VV_{LAX}.

Conclusions: Although exercise-related knee laxity changes were more pronounced in females, there was a subset of both males and females who experienced substantial knee laxity increases during exercise. Whether these individuals are more susceptible to higher-risk lower extremity biomechanics and injury risk later in a game or practice is currently under investigation.

Keywords: soccer | joint | sex comparison | ACL injury | biomechanics | risk factor

Article:

Greater magnitudes of knee joint laxity have been consistently associated with a greater risk of anterior cruciate ligament (ACL) injury in both retrospective (2,11,14,21,26,41) and prospective studies (16,39). Moreover, females have greater magnitudes of knee laxity compared to males, which has been associated with their higher-risk biomechanics (31,34) and compensatory neuromuscular strategies (24,28) during functional tasks. These effects may be exacerbated later in a match or practice because knee joint laxity is reported to increase by as much as 20%–30% above baseline values after 20–30 min of exercise (17,22,25,35–37,40), which is consistent with the time in a game or practice when injury rates are reported to be highest (7,20). However, before moving on to studies that examined the biomechanical consequences of these changes in knee laxity during exercise, much remains unknown about the timing and extent of these knee laxity changes in men and women under relevant, sport-related exercise conditions.

ACL injury typically occurs during sports that involve sudden deceleration and change of direction (e.g., soccer, basketball, and football) (8). However, studies examining knee laxity changes during exercise have primarily focused on sagittal plane activities such as flexion/extension isokinetic contractions (24), stationary cycling (1), forward running (9,17,25,36), or a combination thereof (35). While some have incorporated limited cutting and landing activities into their submaximal running protocols (19,25) or examined changes during multidirectional running (6), only two have measured changes after sport practices (e.g., basketball [36] and cheerleading [22]). As greater anterior knee laxity increases were observed during a 30-min intermittent shuttle run of varying intensities that included plant and cut maneuvers as compared to steady-state treadmill running of equal duration (6), it may be more relevant to examine knee laxity changes during multidirectional activities that better mimic the sport demands when injuries are more likely to occur. Moreover, these studies have primarily focused on sagittal plane knee laxity. Changes in transverse and frontal plane knee laxity may also be important, given the multidirectional nature of sport, particularly because these laxities are proportionally greater in females than males and have been associated with their greater potential for dynamic knee valgus motion (31,33). Although exercise-related changes in transverse plane knee laxity have been reported (5%–14%), they are limited to 30 min of submaximal sagittal plane running (9,37). In sum, multidirectional knee laxity changes have yet to be studied during sport-related multidirectional activities.

Also unknown is the time course of multiplanar knee laxity changes during intermittent sport-related activity and whether males and females change in a similar manner over time. While anterior knee laxity is reported to increase within 20 min of exercise and remain elevated 1 h after activity (17), this study was limited to males during submaximal forward running. Females are reported to have less stiff and structurally weaker ligaments than males (even once

accounting for age, ligament size, and body size), which is thought to result from metabolic/remodeling processes that regulate ligament material properties (3). Females are also reported to have greater multiplanar knee laxity profiles (32) compared to males. Thus, females may experience different patterns of laxity changes during exercise, particularly during intermittent, multidirectional activities where joint structures may come under greater stress. While one study has reported similar laxity changes in males and females during exercise (19), these comparisons were limited to a single measure of anterior knee laxity after a relatively short exercise duration (~20–25 min) that was primary sagittal plane in nature. We are not aware of any studies that have measured time-related changes in multiplanar knee laxity in males and females before, during, and after a sport-related intermittent exercise protocol (IEP) that involves constant changes in speed and direction and that is consistent with the length of a game or practice. Understanding the time-related changes in multiplanar knee laxity during sport-specific exercise could provide important insights into potential changes in joint vulnerabilities during exercise and potential mechanisms by which injury risk increases later in a practice or competitive match.

The purpose of this study was to measure changes in multiplanar knee laxity (i.e., sagittal [AP_{LAX}], frontal [VV_{LAX}], and transverse [IER_{LAX}]) in males and females before and after a dynamic warm-up and every 15 min during and for 1 h after the course of a 90-min IEP that mimics the lower extremity demands of a soccer match. Our expectation was that we would observe multiplanar knee laxity increases within the first 15 min of activity that would continue to increase with exercise duration and would slowly return to baseline during the 1-h recovery. We also expected that females, who have greater laxity and lower ligament mechanical properties, compared to males, would demonstrate greater knee laxity increases during the exercise protocol.

METHODS

Participants were 30 male (20.3 ± 2.0 yr, 1.79 ± 0.05 m, 75.2 ± 7.2 kg) and 30 female (20.6 ± 2.3 yr, 1.67 ± 0.07 m, 61.8 ± 9.0 kg) intercollegiate and club sport athletes who participated in a larger study examining changes in knee joint laxity and lower extremity biomechanics during an IEP. To be included in the study, subjects were consistently engaged in competitive sport activities that included running, cutting, and landing maneuvers for the past 5 yr and who were currently active a minimum of 6 h·wk-1. All subjects had a healthy left knee with no prior history of injury involving the osteochondral surface, ligament, tendon, capsule, or menisci; no known coexisting medical conditions affecting the connective tissue; and no vestibular or balance disorders that could cause them to lose their balance during the functional tasks. Before participation, subjects were informed of study risks and signed a consent form approved by the university's institutional review board. Subjects were asked to refrain from exercise on the day of testing and to 1) avoid moderate to strenuous activity (i.e., activity beyond what they normally and consistently perform), 2) maintain dietary habits common to their precompetition routine, and 3) avoid consuming alcohol for 48 h before testing. All testing for females was completed during the first 10 d of their menstrual cycle to control for hormone-related effects on knee laxity (30). All laxity and biomechanical measures were acquired on the left leg (typically the dominant stance limb when kicking a ball). We chose to consistently test the left limb (versus the dominant stance limb) on all subjects to maximize data collection efficiency during the testing blocks.

Testing protocol

Each participant attended a familiarization session, where they completed a 12-min standardized dynamic flexibility warm-up and performed the Yo-Yo Intermittent Recovery Test Level 1 (YYIR1) (12). Dynamic warming consisted of 3 min of forward and backward jogging, followed by approximately 9 min of dynamic flexibility movements of increasing complexity (e.g., heel–toe walks, backward runs, heel kicks, side shuffles, walking lunges, inward and outward walking hip rotations, and high knees) and forward/backward running at increasing intensities. The YYIR1 is structured similar to a graded exercise test with 15 stages of repeat 20-m shuttle runs and 5-m walking recovery intervals, where running speed (dictated by an audible beep) is steadily increased with each subsequent stage until the subject is no longer able to maintain the pace dictated. The average running speed achieved at the final stage is used to identify the participant's fitness level and to subsequently prescribe their submaximal running speeds for the IEP (4). After the YYIR1, participants were familiarized to all study procedures, including their prescribed running speeds for the IEP. They were then scheduled for their control and experimental test sessions (order counterbalanced), spaced 3–4 d apart.

During the experimental session, participants were instrumented with three independent optical LED markers (Phase Space, San Leandro, CA) secured each to the left foot, shank, thigh, and sacrum using hook and loop material attached to compression shorts and a shank sleeve. Joint centers were determined via the centroid (ankle and knee) (15) and rotational method (hip) (13). Once instrumented, participants completed the same dynamic flexibility warm-up, followed by the IEP. The IEP was designed to simulate the physiological (aerobic, anaerobic) and biomechanical demands (decelerating, cutting, jumping, and landing) of intermittent endurance sports (e.g., soccer), with two 45-min halves and a 20-min half-time intermission (4). The IEP was performed on a gymnasium floor as intermittent shuttle runs consisting of alternating 6 s of submaximal running at varying intensities (jogging, low-intensity running, moderate-intensity running, high-intensity running, and sprinting) followed by 6 s of walking and standing. The different running intensities were achieved by having subjects complete shuttle runs at five different distances (designated by different color cones) from the start line, where they were required to pace their run to reach each distance within the same 6-s window (dictated by a metronome). Thus, each "shuttle" consisted of subjects beginning at the starting line, reaching the designated cone in 6 s (regardless of distance), walking around a second cone and back to the first in 6 s, returning to the starting line in 6 s, and then walking around a cone and back to the starting in 6 s. The distance of each cone (thus, running intensities) from the starting line was established for each subject based on his/her maximum running speed obtained from the YYIR1 (4).

Each 15-min segment of the IEP included two consecutive sets of 6 min of intermitted shuttle runs across the varying intensities, followed immediately by a 3-min testing segment of two maximal 505 agility sprint trials (5), two countermovement jumps, three drop jump landings (34), and four single-leg perturbation trials (27). The 505 agility sprint is a combined sprint and cut task, where subjects completed two up and back 15-m shuttle runs as fast as possible, first cutting off the right foot, then off the left foot. The average speed (recorded in seconds and converted to meters per second) to complete the two trials was recorded for each subject. The

single-leg perturbations consisted of standing in a single-leg stance while restrained by two Kevlar cables attached to the wall, then creating a forward and either internal or external rotational perturbation of the trunk and thigh relative to the lower shank upon cable release that mimicked side step (internal) or crossover (external) cutting maneuvers. For the purposes of this study, only data for the 505 agility test are reported.

After each 15-min exercise/testing segment, subjects reported their ratings of perceived exertion and rested for 90 s (similar in length to a time out), while clinical measures of knee laxity (i.e., AP_{LAX}) were acquired. Thus, except for the knee laxity measurements, performance and biomechanical measures (reported elsewhere) were integrated into the IEP to mimic the stretch–shortening cycle work of match play and to ensure that subjects were constantly moving during the IEP. A total of 13 measurement time points allowed us to examine changes in knee laxity before and after the dynamic warm-up (PreWm, PostWm), every 15 min during the IEP (15 min, 30 min, 45 min, Half, 60 min, 75 min, 90 min) and every 15 min for 1 h after the completion of the IEP (Post15, Post30, Post45, Post60) (see Fig. 1 for schematic). During the 1-h recovery, participants sat quietly between testing segments. The only exception to the described protocol was the measurement of VV_{LAX} and IER_{LAX}. Because clinical devices are not currently available to measure VV_{LAX} and IER_{LAX}, these measures take approximately 10 min to complete and were therefore limited to the PreWm, PostWm, 45 min, 90 min, and Post30 test points when they could be completed during longer rest periods.

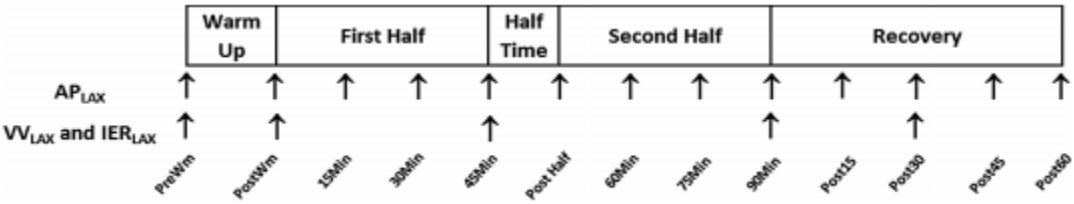

FIGURE 1—Testing time points for laxity measurements before, during, and after the intermittent exercise protocol.

The control session consisted of the same dynamic warm-up, 3-min testing segments (countermovement jumps, drop landings, and single-leg perturbations), and measurement of knee laxity at the same 13 time points as the experimental session. However, the participants did not perform any running segments of the IEP (intermittent shuttle runs or 505 agility sprints). Thus, during the 12.5 min of each 15-min exercise/testing block when shuttle runs and sprints were performed in the experimental session, participants sat quietly for an equivalent period for the control condition.

Laxity measurements

AP_{LAX} was measured as the anterior–posterior displacement of the tibia relative to the femur using the KT-2000™ Knee Arthrometer (MEDmetric Corp., San Diego, CA), which has been shown to accurately track anterior–posterior displacement of the tibia relative to the femur (38). Using standardized techniques per manufacturer guidelines, the arthrometer was placed on the anterior aspect of the leg, with the two sensor pads placed on the patella and tibial tubercle, and the knee positioned in 25° ± 5° of flexion (with each subject consistently positioned at the same angle across time points). Using the force-sensing handle of the arthrometer, three posterior-directed forces were initially applied to the anterior aspect of the tibia to zero the dial, followed

by one trial of three continuous cycles of posterior-to-anterior-directed forces from -90 to 133 N, respectively (per manufacturer audible tones), at a smooth and steady rate. A bubble level fixed to the device confirmed a direct posterior–anterior line of pull. The average of the last two cycles of AP displacements from -90 to 130 N was used for analysis because we have found during pilot testing more stable measurement values when averaging the last two trials as opposed to all three trials. Two experienced testers trained by the same individual confirmed measurement consistency before testing ($ICC_{2,3}$ [SEM] = 0.96 [0.3 mm]; 0.93 [0.4 mm]). All laxity measures within a subject were acquired by the same investigator across all conditions and time points.

VV_{LAX} and IER_{LAX} were measured with the Vermont Knee Laxity Device (VKLD) using established measurement techniques (31). Subjects were positioned in supine with the knee flexed to 20°, the thigh securely fixed, and the foot and ankle flexed 90° and strapped to a foot cradle connected to a calibrated six-degree force transducer. Counterweights were applied to eliminate gravity forces of the limb and to create an initial zero shear load across the tibiofemoral joint. Kinematic data were obtained at 240 Hz with an eight-camera optical system (Impulse, Phase Space, San Leandro, CA), whereas kinetic data were obtained with a force transducer at 500 Hz. Total VV_{LAX} was measured as the angular displacement of the tibia relative to the femur in the frontal plane while applying three continuous 0–10 N·m valgus and varus torque cycles to the distal tibia with a force transducer (Model SM-50; Interface, Scottsdale, AZ) (31). $IER_{LAX}$was measured as the angular displacement of the tibia relative to the femur in the transverse plane by applying three continuous 0–5 N·m internal–external torque cycles about the long axis of the tibia using a T-handle connected to a six-degrees-of-freedom force transducer affixed to the foot cradle (MC3A; Advanced Medical Technology, Inc., Watertown, MA) (31). At each time point, a conditioning trial of three continuous VV or IER torque cycles (to ensure subject relaxation) was followed by a test trial of three continuous VV or IER torque cycles. Consistent with AP_{LAX}, and to maximize measurement consistency, the average VV and IER displacements of the last two cycles of the test trial was used for analysis.

Statistical analyses

To tests our hypotheses, a 2 (sex; male and female) by 2 (condition; exercise and control) by 13 (time; PreWm, PostWm, 15 min, 30 min, 45 min, Half, 60 min, 75 min, 90 min, Post15, Post30, Post45, and Post60) ANOVA with repeated measures on condition and time examined changes in AP_{LAX} between sex and condition over time. Similarly, separate 2 (sex) by 2 (condition) by 5 (time; PreWm, PostWm, 45 min, 90 min, and Post30) repeated-measures ANOVA examined changes in VV_{LAX} and IER_{LAX} between sex and condition over time. Before analyses, independent *t*-tests compared males and females on their baseline AP_{LAX}, VV_{LAX}, and IER_{LAX} (defined as the average PreWm laxity value averaged across control and experimental conditions). If sex differences were observed, the appropriate baseline laxity was included as a covariate in the ANOVA model to account for sex differences in exercise-related changes that may simply be proportional to their baseline magnitude. Significant time main effects were further explored in *post hoc* analyses using pairwise comparisons (Bonferroni corrected). Significant interactions were explored using simple main effects testing. Significance level was set *a priori* at $P < 0.05$. On the basis of a total sample size of 60 subjects (30 for each sex), an *a priori* [alpha] level of 0.05 and a correlation among repeated-measures conservatively estimated at $r = 0.5$, we determined we had 80% power to detect a medium effect size ($f > 0.27$) for overall

group main effects, and a small effect size (f > 0.11–0.15) for time main effects and interactions for group by time and group by time by condition.

RESULTS

Complete data were obtained on 29 females and 30 males; 1 female withdrew from the IEP after the 15 min mark and was therefore excluded from the analyses. Females had greater baseline knee laxity than males for VV_{LAX} (9.7° ± 2.9° vs 6.8° ± 2.0°, P < 0.001) and IER_{LAX} (28.2° ± 6.1° vs 22.8° ± 4.9°, P < 0.001) but not AP_{LAX} (9.1 ± 1.9 vs 8.5 ± 1.8 mm, P = 0.190). As such, the respective baseline value was included as a covariate when examining sex differences in exercise-related VV_{LAX} or IER_{LAX} changes.

For AP_{LAX}, there was a sex by condition by time interaction (P = 0.037). *Post hoc* analyses indicated that sex differences in AP_{LAX} were observed during the IEP (P = 0.002) but not during the control condition (P = 0.592; Fig. 2). During the IEP, AP_{LAX} increased in females at 15 min, 30 min, 45 min, 60 min, 75 min, and 90 min compared to PreWm (all P < 0.004). Peak values obtained at the end of the first and second halves (10.1 ± 2.0 and 10.1 ± 2.1 mm, respectively) were 12% greater than PreWm (9.0 ± 1.8 mm). 90 min was also greater than PostWm values. Although no recovery point differed from PreWm or PostWm, the Post30, Post45, and Post60 recovery time points were lower than the peak values obtained near the end of each half of the IEP. In males, AP_{LAX} increased less than 5% and no subsequent time point differed from PreWm. No recovery point differed from PreWm, but Post45 values were lower than 60 min and 75 min, and Post60 values were lower than all values measured during exercise. On the basis of these time-related changes, females had greater AP_{LAX} than males did at 15 min, 30 min, 45 min, 90 min, Post15, and Post60 time points. For descriptive purposes, and to ensure these changes did not simply reflect changes in knee joint behavior due to fatigue, we plotted the relative changes in AP_{LAX} and 505 total sprint speed (meters per second, used in this study as an index of lower extremity neuromuscular fatigue) and observed relatively low correlations between laxity changes and fatigue-related changes over time (Fig. 3).

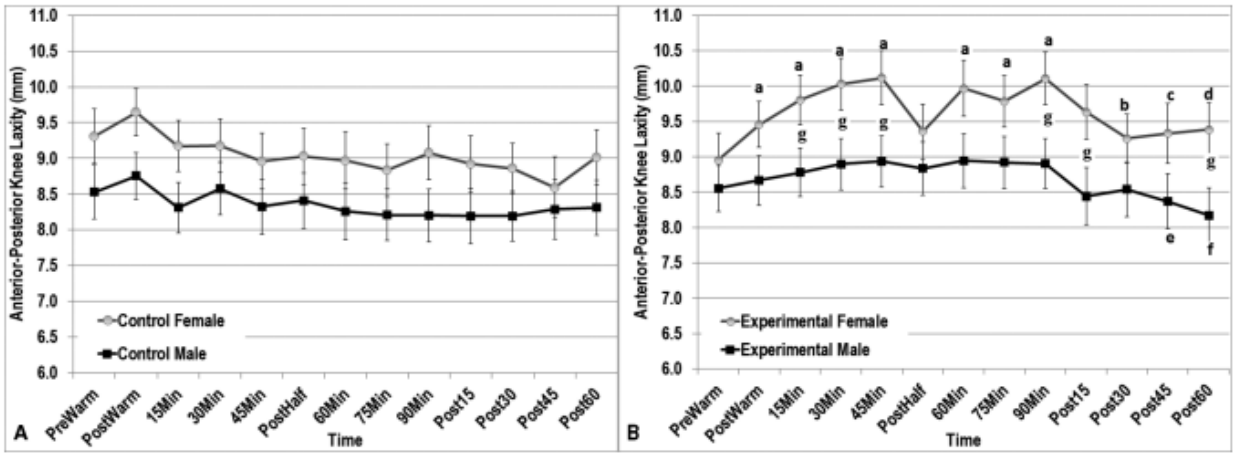

FIGURE 2—Sex differences in time-related changes in experimental (A) but not control (B) conditions for AP_{LAX}. Symbols indicate value is [a]greater than PreWm; [b]less than 30 min, 45 min, and 90 min; [c]less than 45 min, 60 min, and 90 min; [d]less than 30 min and 45 min; [e]less than 60 min and 75 min; [f]less than all exercise time points; and [g]greater in females than males at the designated time point.

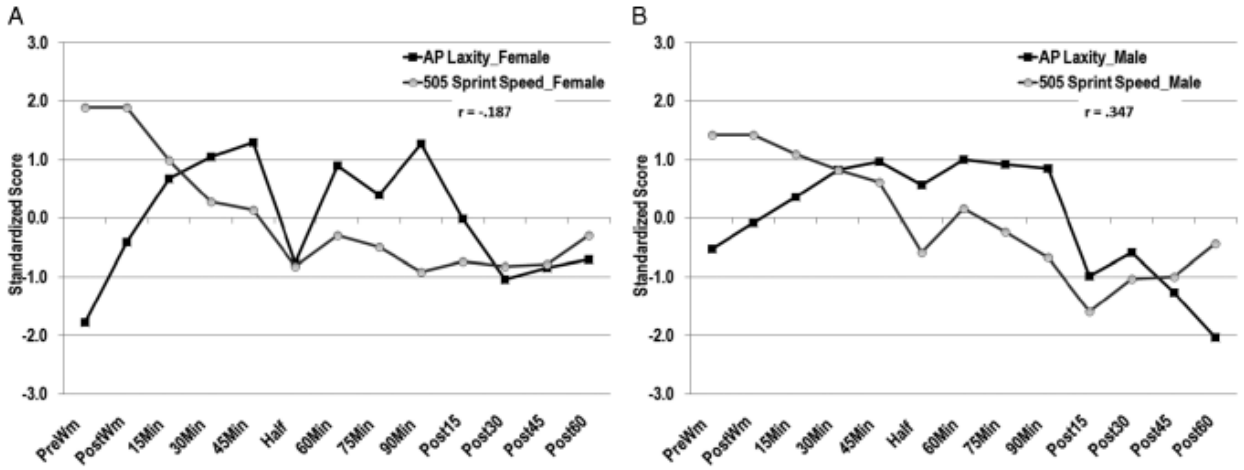

FIGURE 3—Correlations between relative changes in AP_{LAX} and relative changes in 505 total sprint speed (index of neuromuscular fatigue) in females (A) and males (B).

Table 1 lists the adjusted means (i.e., after adjusting for baseline laxity values) for VV_{LAX} and IER_{LAX} stratified by sex, condition, and time. A sex by condition by time interaction was observed for VV_{LAX} ($P = 0.034$). Similar to AP_{LAX}, sex differences were observed for the IEP ($P = 0.013$) but not control condition ($P = 0.549$). During the IEP, females increased their VV_{LAX} at 45 min, 90 min, and Post30 compared to PreWm (all $P < 0.013$), with peak increases at Post30 being 10% greater than those at PreWm (Table 1). This resulted in greater VV_{LAX} values in females compared to males at the 90 min and Post30 time points, although the adjusted mean value was lower for females at PreWm. VV_{LAX} did not increase in males at any time point ($P = 0.803$). Once controlling for baseline IER_{LAX}, IER_{LAX} increased over time ($P = 0.007$), with all measured time points being greater than PreWm (mean ± SE: 25.4° ± 0.0° PreWm < 26.5° ± 0.3° PostWm, 26.9° ± 0.4° 45 min, 27.3° ± 0.4° 90 min, 26.9° ± 0.4° Post30). Peak increases observed at 90 min were 7.0% higher than PreWm and 2.6% higher than those at PostWm ($P < 0.037$). There was no evidence of IER_{LAX} values decreasing below exercise values by Post30. These time-related changes did not differ by sex ($P = 0.549$), condition ($P = 0.434$), or sex by condition ($P = 0.866$).

TABLE 1. Means ± SE for frontal (VV_{LAX}) and transverse (IER_{LAX}) laxity stratified by sex, condition, and time, after adjusting for sex differences in baseline values.

	Condition	PreWm	PostWm[a]	45 Min[a]	90 Min[a]	Post30[a]
VV_{LAX} (°)						
Control	Male	7.8 ± 0.2	8.6 ± 0.2	8.2 ± 0.3	8.2 ± 0.3	8.1 ± 0.3
	Female	8.7 ± 0.2	8.7 ± 0.2	8.7 ± 0.3	8.9 ± 0.3	8.6 ± 0.3
Experimental	Male	8.7 ± 0.2	8.3 ± 0.2	8.5 ± 0.3	8.5 ± 0.3	8.4 ± 0.3
	Female	7.8 ± 0.2[b]	8.4 ± 0.2	8.9 ± 0.3[c]	9.0 ± 0.3[b,c]	9.2 ± 0.3[b,c]
IER_{LAX} (°)						
Control	Male	25.8 ± 0.5	26.5 ± 0.8	27.4 ± 0.8	27.6 ± 1.1	26.7 ± 0.8
	Female	25.2 ± 0.5	26.1 ± 0.5	26.6 ± 0.8	27.7 ± 0.7	26.8 ± 0.9
Experimental	Male	25.9 ± 0.5	26.6 ± 0.8	27.4 ± 0.8	27.4 ± 1.0	27.0 ± 0.8
	Female	25.1 ± 0.5	27.0 ± 0.5	26.4 ± 0.8	26.4 ± 0.7	26.9 ± 0.9

[a]IER_{LAX} greater than PreWm (time main effect).
[b]Females ≠ males.
[c]Greater than PreWm value.

The largest mean change we observed at any time point was 0.7 ± 1.0 mm for AP_{LAX} ($F = 1.1 ± 1.0$ mm, M = 0.4 ± 0.9 mm), 0.5° ± 1.7° for VV_{LAX} ($F = 1.0° ± 1.9°$, M = 0.1° ± 1.4°), and 1.7° ± 4.9° for IER_{LAX} ($F = 1.4° ± 4.2°$, M = 2.1° ± 3.7°). These mean values hide much of the variability in the magnitude of knee laxity change each individual experienced over time, which

ranged from -0.10 to 5.9 mm for AP_{LAX}, -1.7° to 5.7° for VV_{LAX}, and -4.1° to 13.3° for IER_{LAX} (see Fig. 4 for box plots of AP_{LAX}change values that depict this variability). This intersubject variability was observed in both sexes, with a larger proportion of females having appreciable knee laxity changes during exercise (i.e., >=1 SD of the mean) for AP_{LAX} and VV_{LAX} (e.g., 33% of females vs 10% of males had increases in AP_{LAX} >= 1.9 mm and VV_{LAX} >= 2.8) but not for IER_{LAX} (e.g., 33% of each sex had IER_{LAX} increases >=5.2°).

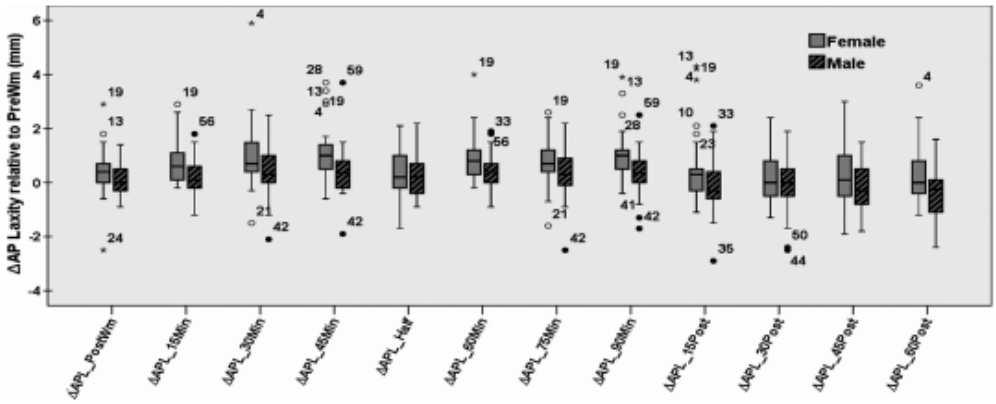

FIGURE 4—Box plots noting the intersubject variability in exercise-related changes in AP_{LAX} at each time point (values represent the change in laxity at each time point from PreWm). The *box* represents the interquartile range (middle 50%), with the *horizontal line* indicating the median value and the *whiskers* extending to 1.5 times the interquartile range. *Circles* denote outliers with laxity changes between 1.5 and 3.0 times the interquartile range; *asterisks* denote outliers with laxity changes more than three times the interquartile range.

DISCUSSION

Our primary findings revealed exercise-related increases in multiplanar knee laxity that were more pronounced in females than in males for AP_{LAX} and VV_{LAX} but not IER_{LAX}. Within females, AP_{LAX} increased within the first 15 min of each half (15 min and 60 min, respectively), peaked by the end of each half (~12% increase), and remained near exercise values until 30–45 min after exercise. VV_{LAX} increased similarly at the end of each half (~10%) and remained elevated 30 min after exercise. In both sexes, IER_{LAX} increased after the warm-up and remained elevated at the end of each half and at 30 min after exercise (~6.5% increase). While on average, we observed no significant increases in AP_{LAX} and VV_{LAX} in males, there were a small proportion of males (~10%) who experienced substantial knee laxity increases that were of similar magnitude to females.

When comparing our findings with prior literature (Table 2), the magnitude of change in laxity we observed during intermittent exercise tended to be less than what has been previously reported for IER_{LAX} and AP_{LAX} (comparisons not available for VV_{LAX}). However, differences in methodological and physiological factors among studies may explain these findings. While our mean change of 1.7° in IER_{LAX} is smaller than what Stoller et al. (37) reported in 13 males after a 5.6-km running course (6.5°), they measured IER_{LAX} at twice the applied torque (±10 N·m) and with the knee flexed 90°. Our values are more similar to those of Johannsen et al. (9) who measured IER_{LAX} at ±5 N·m in 90° knee flexion in 20 distance runners (11 males and 9 females) after 30 min of a submaximal run, reporting a 5% increase from preexercise. Our mean increases in AP_{LAX} were also toward the lower end of other reports for anterior knee laxity (0.48–2.3 mm) (6,17,19,22,25) and AP_{LAX} (1.0–1.7 mm) (9,35,36). While these studies varied widely in type,

intensity, and duration of exercise protocols used, it seems that larger changes have been observed after submaximal, steady-state forward running activities (1.7–2.1 mm) (9,17) than more exhaustive (0.48–1.5) running (6,17,25,35,36) or ballistic activities (change of direction, cutting, and jumping; 0.82–1.5 mm) (6,19,22,36). Although this overall trend is contrary to the work by Gleeson et al. (6), the smaller laxity changes we observed during an IEP that incorporated multiple speed and direction changes and maximal sprinting and jumping activity are consistent with this trend.

TABLE 2. Prior studies reporting exercise-related knee laxity changes.

Study	Subjects	Exercise Protocol	Measure (Baseline Value)	ΔPre-to-Post
Belanger et al. (1)	18 female collegiate or high-level recreation athletes	20-min stationary bike	AKL at 134 N (4.5 ± 1.9)	0.24 mm (NS)
Gleeson et al. (6)	8 male semiprofessional soccer players	Various 9600-m running activities	AKL at 200 N	
		1) Intermittent-intensity shuttle run	(2.0 ± 1.0)	0.88 mm[a]
		2) Continuous-intensity shuttle run	(1.9 ± 0.9)	0.82 mm[a]
		3) Continuous-intensity treadmill run	(2.0 ± 0.9)	0.48 mm[a]
Johannsen et al. (9)	20 (11 males and 9 females) long-distance runners	30-min submaximal running	APL at 100/150/200 N	
			(10.9 mm at 100 N)	1.7 mm[a]
			(13.6 mm at 150 N)	2.3 mm[a]
			(15.6 mm at 200 N)	2.2 mm[a]
Nawata et al. (17)	10 male VB players	40 min submaximal treadmill run	AKL/PKL at 133 N	
	10 male triathletes	Triathlon race	(6.3 ± 2.1/2.7 ± 0.9 mm)	2.1[a]/0.1 mm
			(6.8 ± 1.4/3.2 ± 1.0 mm)	1.5[a]/−0.1 mm
Pollard et al. (19)	12 males/12 females physically active	15 min treadmill (self-selected moderate to hard intensity), followed by 2-min grapevine weave, 2 min left–right cutting, and 25 jump downs from 0.46 m	AKL at 89 N	
			(M: ~3.0 mm)[b]	M: ~1.2 mm[a,b]
			(F: ~4.2 mm)[b]	F: ~1.2 mm[a,b]
Rowe et al. (22)	17 (9 males and 8 females) cheerleaders	2-h practice composed of 1.5-mile run, 0.5-mile walk, tumbling, dance, pyramids, tosses, and partner stunts	AKL at 67/89/133 N	
			(4.0 ± 2.0 mm at 67 N)	1.3 mm[a]
			(4.9 ± 2.0 mm at 89 N)	1.2 mm[a]
			(5.5 ± 2.0 mm at 133 N)	1.5 mm[a]
Rozzi et al. (23)	34 (17 males/17 females) collegiate BKB and SOC players	Maximal effort concentric flexion–extension contractions to 25% fatigue (~170 reps)	AKL at 133 N	
			(M: 4.8 ± 1.5 mm)	0.7 mm
			(F: 6.1 ± 1.5 mm)	0.0 mm
Sailors et al. (25)	9 females after ACL-R (uninjured side)	30-min agility running (mostly forward running with some zigzag cutting)	AKL at 130 N	
			(4.4 ± 2.8 mm)	1.3 mm[a]
Skinner et al. (35)	10 male US Navy Seals	2-mile warm-up, 6.5-min run, intermittent fatigue protocol of three alternating 6.5-min mile runs and 0.25-mile sprints, then 20-min rest, 35 reps of isokinetic exercise at 180°·s^{-1} were interspersed between each activity on R leg only	AKL/PKL at 89 N	
			(7.3 ± 1.2/2.9 ± 0.7 mm – right)	0.2/0.4 mm – right
			(7.4 ± 1.3/3.1 ± 0.6 mm – left)	0.6[a]/0.4 mm – left
Steiner et al. (36)	10 female BKB players	Various activities	APL at 133 N	
	24 male powerlifters	1) Normal basketball practice	(6.8 ± 2.5 mm)	1.3 mm[a]
	12 (11 males and 1 females) distance runners	2) Series of power squats	(6.2 ± 2.1 mm)	0.1 mm
		3) 10-km road race	(5.0 ± 2.2 mm)	1.0 mm[a]
Johannsen et al. (9)	20 (11 males and 9 females) long-distance runners	30-min submaximal running	IER at 5 N·m (90°)	
			(17.9° ± 4.9°)	0.9°
Stoller et al. (37)	13 males nonsedentary (mostly runners)	5.6-km running course (~30 min)	IER at 10 N·m (90°)	
			(45.3° ± 6.3°)	6.5° ± 3.1°[a]

[a]Significant change reported by authors.
[b]Values estimated from article figures (actual values not reported).

A potential explanation for smaller laxity changes during high-intensity intermittent activities may be an involuntary increase in resting muscle tension and stiffness (i.e., persistence in actin and myosin cross-bridges) that can occur with fatiguing exercise. This mechanism is thought to facilitate resistance to stretch perturbations and augment force production (i.e., postcontractile potentiation) in the presence of fatigue (18). Alternately, as the structure of the IEP resulted in laxity measures being taken immediately after maximum sprinting and jumping activities, it may have been more difficult for our subjects to volitionally relax their muscles during the laxity measurements, despite our efforts to maximize relaxation through consistent verbal instruction. In support of this premise, Skinner et al. (35) reported smaller, insignificant changes in anterior knee laxity on the right versus left leg after a running fatigue protocol, where the right leg was

subjected to maximal isokinetic contractions before postexercise laxity measurements. While more work is needed to fully understand potential exercise- and task-specific effects, these findings suggest that knee laxity changes during intermittent sport-related exercise may be less than what is typically observed during submaximal forward running.

Despite the relatively small mean knee laxity increases observed during the IEP, individual subjects varied widely in the actual magnitude of knee laxity increases they experienced across anatomical planes (Fig. 4). This variability was observed in both sexes, with a larger proportion of females having appreciable knee laxity increases compared to males for AP_{LAX} and VV_{LAX} but not for IER_{LAX}. The underlying cause of this intersubject variability is unknown but may include differences in training effects, movement patterns, joint geometry, lower extremity alignment, or anthropometrics that have the potential to differentially influence the multidirectional stresses placed on the soft tissue structures about an individual's knee during sport activity. Individual differences in lower extremity lean muscle mass and knee ligament mechanical properties, which are known to influence knee joint behavior (3,29), may also be differentially affected during exercise. Further research is needed to determine which factors promote larger knee laxity increases during exercise in some individuals more than others, and whether this range of intersubject variability has a clinically meaningful effect on an individual's static and dynamic joint stability during exercise.

Consistent with our hypothesis, females experienced greater AP_{LAX} and VV_{LAX} increases during exercise than males. Males and females have been rarely compared in the same study. However, when reported in separate studies, the laxity increases observed in males (range = 0.5–2.1 mm AP_{LAX}; 6.5° IER_{LAX}) (6,17,19,37) seem to be of similar magnitude to those reported in females (range = 1.2–1.3 mm AP_{LAX}) (19,25,36). As prior studies are based on 13 males or fewer (6,17,19,37), the lack of changes we observed in our 30 males is likely not attributable to statistical power. Pollard et al. (19) is the only study that we are aware of that has directly compared males and females under the same exercise conditions, and they reported significant increases in anterior knee laxity from before to after exercise that were similar in females and males (~1.2 mm). It is difficult to directly compare our results to their study because they measured anterior knee laxity at a lower force load (89 N) in moderately active subjects (collegiate athletes excluded) during an exercise protocol (15-min treadmill run, followed by 4 min of weaving and cutting and 25 jump downs) of shorter exercise duration (~20–25 min). It is possible that our more athletic subjects had different stiffness characteristics around the joint (e.g., increase muscle strength and mass around the knee) (10) that may have allowed them to better resist joint displacements, thus explaining the smaller exercise-related laxity changes we observed (i.e., 12% change in AP_{LAX} from -90 to 130 N as opposed to their ~20% change in anterior knee laxity at 89 N). In support of this premise, the two studies that enrolled highly fit male athletes (6,35) also observed smaller changes in knee laxity (range = 0.1–0.9), which were not always significant. However, this does not fully explain the greater laxity changes we observed in females compared to males, as females were also quite fit. As females are reported to have less stiff and structurally weaker ligaments compared to males (3), experience greater joint displacements under similar applied loads (32), and have less available muscle about the joint to resist joint displacements (10), it may simply be that sex differences became more apparent at the higher force at which we obtained our AP_{LAX} measures (130 vs 89 N). The potential implications of these sex-related differences in knee laxity increase during exercise are that females may have

a lesser ability to resist joint displacements to externally applied loads during prolonged sport-related activity. The biomechanical implications of these changes are currently under investigation.

The time-related knee laxity increases we observed were largely consistent with our hypothesis. Previous research indicates that knee laxity increases can occur at relatively low thresholds of exercise intensity within the first 20 min and can remain elevated for as much as 1 h after exercise (17,37). Our findings are in general agreement with these data. IER_{LAX} and AP_{LAX}increased by the end of the dynamic warm-up or within the first 15 min of starting the IEP, respectively. Given these early changes and reports of similar magnitudes of change with low versus high exercise intensities (17), knee laxity increases during exercise are more likely attributed to the viscoelastic response of the ligament and capsular structures to repetitive joint loading rather than a result of decreased muscle tone caused by muscular fatigue (9,17). Viscoelastic effects are further supported by reports that exhaustive strength and conditioning-type activities of shorter duration (weightlifting, isokinetic knee extension/flexion to fatigue) do not result in measurable increases in joint laxity (1,23,36). Further, when plotting the relative changes in AP_{LAX} and 505 total sprint speed (used in this study as an index of lower extremity neuromuscular fatigue), we observed relatively low correlations (Fig. 3). Thus, these knee laxity increases seem to be a normal physiological response to tissue warming with exercise that may influence knee joint behavior (e.g., joint biomechanics) in a way that is independent of fatigue-related effects. This may represent an interesting paradox that, while this "loosening" of the joint with tissue warming may help facilitate efficiency of movement during exercise, it may also increase the vulnerability of the joint to displacing loads. This may be particularly problematic later in a match or practice when both fatigue and knee laxity continues to increase.

In summary, we observed greater changes in knee laxity in females compared to males during intermittent exercise consistent with the intensity, movement tasks, and duration of relevant sport activity. Greater magnitudes of knee laxity have consistently been associated with a greater risk of ACL injury and may disrupt normal joint biomechanics during weight bearing activity (31,34). However, these later investigations have been performed under resting conditions, which do not account for further changes in knee joint laxity that normally occur with exercise. Understanding the biomechanical implications of these exercise-related knee laxity changes may be important because acute laxity changes of similar magnitude during a female's menstrual cycle are reported to increase their potential for high-risk knee joint biomechanics (33). Moreover, the peak increases we observed at the end of each half of the IEP in the current study coincides with the time in a practice or match when injury rates are reported to be the highest (7,20). Work is ongoing to determine whether the magnitude of knee laxity increases we observed during exercise is sufficient to increase the potential for higher-risk knee joint biomechanics during sport activity. Of particular concern may be the subset of both males and females who show substantially larger exercise-related knee laxity increases compared to others and who may be particularly prone to greater joint displacements and higher-risk biomechanics later in a practice or game. Thus, future research should also examine the factors that contribute to this intersubject variability and the potential for some individuals to increase their knee laxity more than others. Ultimately, it will be important to determine whether these intersubject differences in knee laxity changes (and subsequently biomechanical changes) impact one's injury risk potential.

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