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The Effect of Direction and Reaction on the Neuromuscular and Biomechanical Characteristics of the Knee During Tasks That Simulate the Noncontact Anterior Cruciate Ligament Injury Mechanism

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Background: Jumping and landing tasks that have a change in direction have been implicated as a mechanism of noncontact anterior cruciate ligament injury. Yet, to date, neuromuscular and biomechanical research has focused primarily on straight landing tasks during planned jumps.

Hypothesis: Lateral and reactive jumps increase the neuromuscular and biomechanical demands placed on the anterior cruciate ligament, and women perform these tasks differently from men.

Study Design: Descriptive laboratory study.

Methods: A total of 18 male and 17 female healthy high school basketball players underwent an analysis of the knee during planned and reactive 2-legged stop-jump tasks in 3 different directions that included novel methodology to incorporate a reactive component. Ground-reaction forces, joint kinematics, joint kinetics, and electromyographic activity were assessed during the tasks.

Results: Jump direction and task (planned or reactive) significantly affected joint angles, ground-reaction forces, knee joint moments, and proximal anterior tibia shear forces; female players demonstrated different kinematic, kinetic, and electromyographic characteristics during these tasks.

Conclusion and Clinical Relevance: Jump direction significantly influenced knee biomechanics, suggesting that lateral jumps are the most dangerous of the stop-jumps. Reactive jumps were also significantly different, suggesting differences between planned laboratory experiments and actual athletic competition. The results of this study indicate that directional and reactive jumps should be included in research methodology and injury-prevention programs.

Keywords: anterior cruciate ligament; biomechanics; knee

Examination of the risk factors for and prevention of anterior cruciate ligament (ACL) injuries has received considerable attention during the past decade because of the relatively large number of injuries that occur each year.[39] Patients who have suffered this injury must endure a lengthy and costly rehabilitation with long-term consequences that can lead to a decrease in knee function and quality of life.[43] The majority of ACL injuries occur during sports participation and are a result of a noncontact mechanisms of injury.[6,43] This type of ACL injury occurs at a significantly higher rate in female athletes,[1,13,42] which has encouraged the development of injury-prevention training programs.[7,20,41]

Neuromuscular and biomechanical characteristics identified during simulated sports tasks have been suggested as potential risk factors for the increased injury rates observed in female athletes[24] and are the target of the previously mentioned training programs. Numerous researchers

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have investigated the differences between men and women performing landing, jumping, and cutting activities.[10,18,22,30,31,46,52] For the majority of these laboratory studies, the subjects had knowledge of the specific task to be performed before initiating the movement. This type of knowledge potentially allows the subjects to preplan movement patterns and may not reflect movement patterns performed in competition during which athletes must react to unanticipated events.[4] Although a few studies examining unanticipated athletic tasks have been performed,[4,18,46] it remains unclear if the neuromuscular, kinematic, and kinetic characteristics during anticipated movement tasks are the same as those during unanticipated (reactive) movement tasks. Studies of this nature require the development of novel methodology that simulates these unanticipated tasks during activities that have been implicated in noncontact ACL injuries.

Although the specific mechanism of noncontact ACL injuries has not been identified, researchers have described common aspects of this injury through athlete interviews and analysis of videotapes.[6,38,45] McNair et al[38] concluded that noncontact ACL injuries typically occur at footstrike, with the knee close to full extension. Most of these injuries also occurred when the subjects were performing movements that caused a rotation of the tibia on the femur. Boden et al[6] used questionnaires and video to analyze noncontact ACL injuries. They reported that most of the injuries occurred during tasks that included a sharp deceleration, a change in direction, and/or during landing on 1 or 2 legs. Most recently, Olsen et al[45] examined videotapes and interviewed patients who had suffered noncontact ACL injuries. They reported that all of the injuries occurred via 1 of 2 mechanisms, a plant-and-cut or a 1-legged jump-shot landing. Both of these mechanisms included a forceful valgus, during a deceleration activity, with the knee close to full extension.

The first purpose of this study was to examine the neuromuscular and biomechanical characteristics during jumping and landing tasks that incorporate both a directional change and a deceleration component similar to those tasks that have been implicated in noncontact ACL injuries. The second purpose of this study was to determine if these same tasks would be performed differently under conditions that prevented the subject from knowing the specific task to be performed before initiating the movement. The final purpose of this study was to determine if women perform the reactive jumps and the lateral jumps to the left differently from men. These comparisons were chosen based on the relative lack of literature examining unplanned tasks and the similarity between lateral jumps to the left and those tasks implicated in noncontact ACL injuries by Olsen et al.[45] We hypothesized that both jump direction and task (planned vs reactive) would significantly affect ground-reaction forces, knee kinematics, knee joint resultant moments and forces, and muscle activation. For the comparisons between genders, we hypothesized that female subjects would use knee landing strategies and muscle activation patterns different from those used by male subjects that would result in greater ground-reaction forces, knee joint resultant moments, and knee joint resultant forces.

METHODS

Subjects

A total of 35 healthy high school basketball players (18 male and 17 female) were recruited from local schools. All subjects were currently participating on organized basketball teams at least 3 times per week at the time of testing. The mean age, body mass, and height of the male subjects were 16.4 ± 1.4 years, 72.8 ± 9.0 kg, and 1.80 ± 0.08 m, respectively. The mean age, body mass, and height of the female subjects were 15.9 ± 1.1 years, 63.8 ± 10.0 kg, and 1.70 ± 0.07 m, respectively. All subjects were right leg dominant, based on preferred kicking leg.[44] Subjects were excluded from the study if they had a history of serious musculoskeletal injury, any musculoskeletal injury within the past 6 months, or any disorder that interfered with sensory input, musculoskeletal function, or motor function. Before participation, all subjects provided written informed consent in accordance with the University's Institutional Review Board.

Instrumentation

Three-dimensional (3D) coordinate data of the retroreflective markers during the stop-jumps were collected and calculated using a 3D optical capture system (Peak Performance Technologies Inc, Englewood, Colo). This motion-analysis system includes 6 high-speed (120 Hz) optical cameras (Pulnix Industrial Product Division, Sunnyvale, Calif) instrumented and synchronized using Peak Motus software (version 7.2, Peak Performance Technologies Inc). Ground-reaction force data during the jump tasks were collected at 1200 Hz by 2 force plates (Kistler Corp, Worthington, Ohio) that were located within a custom-built flooring system in which the force plates were flush with the surrounding surface. Surface electromyographic (EMG) signals were collected at 1200 Hz via an 8-channel telemetric system (Noraxon USA Inc, Scottsdale, Ariz). The EMG signals were recorded using silver-silver chloride, pregelled bipolar surface electrodes (Medicotest Inc, Rolling Meadows, Ill), and EMG data during a maximum voluntary isometric contraction (MVIC) were collected for the knee flexors and extensors with the Biodex System 3 Multi-Joint Testing and Rehabilitation System (Biodex Medical Inc, Shirley, NY).

Experimental Task

The technique for the stop-jump task consisted of the following: (1) an initial starting point measured as 40% of the subject's height from the edge of the force plates, (2) a 2-legged broad jump with a 2-legged landing on the force plates (1 foot on each), and (3) immediate jump for maximum vertical height (vertical jumps) or maximum horizontal distance (left and right jumps) (Figure 1). To include a reactive component to the stop-jump tasks, a laser coupled with a photocell was instrumented into the experimental setup. A 19-inch flat-screen monitor that provided the visual cue for the jump direction was placed directly in

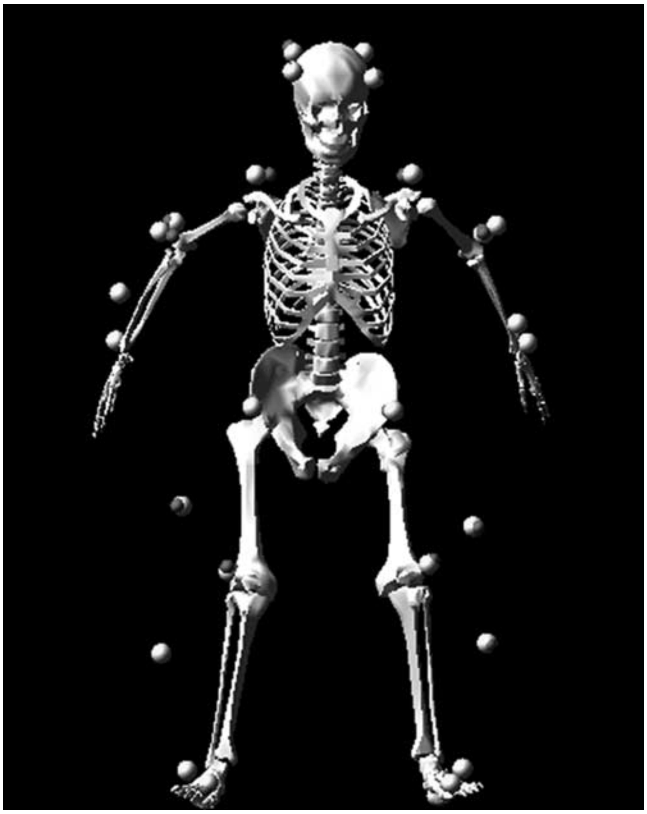

Figure 1. Computer model of subject performing the stop-jump task. Only the right leg was analyzed. Jumps to the subject's right side indicate jumps to the lateral aspect of the right knee, and jumps to the subject's left side indicate jumps to the medial aspect of the right knee.

front of the subjects. The reactive task visual cue was controlled by a customized software program designed in LabView (version 6, National Instruments, Austin, Tex), which received the voltage signal from the photocell. The positioning of the laser photocell trigger was standardized for each subject and was measured as 30% of the subject's standing height in front of the force plates at the height of the subject's fibular head. During the initial jump, the subject passed through the laser beam and interrupted the voltage signal. This signal interruption prompted the LabView program to create the visual cue for the jump direction.

Experimental Procedure

After written consent was obtained, anthropometric measurements were recorded for each subject. They included height and weight, segmental lengths and circumferences of the thighs and shanks, diameters of the ankles and knees, feet length and width, lateral malleoli height, and pelvic width. The stop-jump tasks were then demonstrated to each of the subjects. Limited instructions were given to not affect the performance of the task. Subjects were instructed to begin each task at the designated starting point, land with 1 foot on each force plate, and then immediately jump off the force plates in the designated direction (left, right, or vertical). Subjects were told to jump as high as possible for the vertical jumps and as far possible for the left and right jumps. All subjects were allowed to practice each of the jumps until they were comfortable with the task.

Surface EMG activity was collected bilaterally on the vastus lateralis and semitendinosus muscles. Surface electrodes were placed over the appropriate muscle belly in line with the direction of the fibers with an interelectrode distance of approximately 20 mm. Electrode sites were shaved, abraded, and cleaned with isopropyl alcohol to reduce impedance. Electrode placement sites were based on the work of Delagi and Perotto.[14] A single ground electrode was placed over the anterior aspect of the tibia just distal and medial to the tibial tuberosity. All electrode sites were located via palpation of each subject's anatomy and were confirmed after application of electrodes through visual inspection of signals on the oscilloscope during standardized manual muscle testing.[28]

For each muscle being analyzed, EMG activity during a 5-second MVIC was collected. These data were processed and used for normalization of the corresponding muscle's EMG activity during the dynamic task. Subjects were seated in the chair of a Biodex System 3 Multi-Joint Testing and Rehabilitation System (Biodex Medical Inc). Straps were used to secure the torso, pelvis, and thigh of the leg performing the MVIC. These straps were secured tightly to minimize accessory movements and to isolate the knee joint. The leg attachment of the dynamometer was secured to the shank of the subject with the tibia pad located approximately 2 finger widths above the lateral malleolus. The axis of the dynamometer was positioned so that it was aligned with the axis of rotation of the knee being tested, which was positioned in 60° of flexion.

A total of 15 retroreflective markers were used for data collection of 3D coordinate data during the single-leg stop-jump task. The marker system used was based on research by Kadaba et al,[27] as developed at the Helen Hayes Hospital in New York. Retroreflective markers were placed bilaterally over the second metatarsal head, posterior aspect of the heel, lateral malleolus, femoral epicondyle, anterior superior iliac spine, and the L5-S1 disk space. The markers were secured to the subject with double-sided tape. Four other markers were attached to wands and secured bilaterally to the lateral aspect of the subject's thigh and shank with straps, prewrap, and athletic tape, paying careful attention to the locations of the EMG electrodes to prevent compression or interference with placement.

Data Collection

After the retroreflective marker setup, subjects were allowed to practice a series of stop-jumps designed to familiarize themselves with the reactive task. Each subject practiced 2 reactive jumps in each direction (total of 6 jumps). Jump order was randomly assigned in 5 sets of 6 jumps each, using a Latin square design setup so that each of the jumps (3 directions [left, vertical, and right] and 2 conditions [planned and reactive]) was performed in each of the

5 sets. Subjects performed a total of 30 jumps with at least 30 seconds of rest between each jump. Subjects were also given 1 minute of rest after each set of 6 jumps. Total testing time for all the jumps was approximately 30 minutes.

Data Reduction

Raw analog data from the force plates were used to calculate the ground-reaction force data for each jump trial. The raw coordinate data were filtered using an optimized cutoff frequency.[26] The ground-reaction forces were filtered using a fourth-order Butterworth filter at a cutoff frequency of 100 Hz. The anatomical joint angles were calculated to examine clinically applicable angles and were based on studies by Chao[9] and Grood and Suntay.[19] An inverse dynamics procedure was used to calculate the joint kinetic data during the stop-jump tasks. The joint resultant moment and forces calculated using this procedure were the estimated external moments and forces and were based on the ground-reaction forces and segment inertial forces.[40] Joint resultant forces were normalized to body weight, and joint resultant moments were normalized to a product of body weight and height.[40,54] All of the kinematic and kinetic calculations were performed in the Kinecalc module of the Peak Motus software package (Peak Performance Technologies Inc) and were based on the work of Vaughan et al.[53]

Joint kinematic data, joint kinetic data, and ground-reaction force data were exported to Matlab (release 12, The MathWorks, Natick, Mass) for identification of the variables of interest. The ground-reaction force data were used to calculate the maximum posterior ground-reaction force (Figure 2) during the initial-stance phase of the stop-jump tasks. This point was then identified in the joint kinetic and kinematic data to determine the anterior tibia shear force, knee flexion-extension moment, knee valgus-varus moment, knee flexion-extension angle, and the knee valgus-varus angle at the point of maximum deceleration. The maximum values for each of these variables were also analyzed. In addition, the peak vertical ground-reaction force and peak posterior ground-reaction force (PPGRF) were also analyzed. Data were averaged across 5 trials.

Raw analog data from the MVICs, synchronized raw analog data from the stop-jump trials, and the ground-reaction force data from the stop-jump trials were imported into Matlab for data processing. The mean value of each MVIC was used for normalization of the EMG during the stop-jump trials.[55] Both the MVIC and trial EMG data were processed with a linear envelope before normalization using a Butterworth filter (fourth-order, zero-phase shift, cutoff frequency of 12 Hz). The point of maximum posterior ground-reaction force (maximum deceleration of the body) was identified in each jump trial using the ground-reaction force data. From this reference point, the integrated EMG (IEMG) was calculated for each muscle for the 150 milliseconds before maximum deceleration of the body. In addition, a vastus lateralis to semitendinosus cocontraction value was calculated, based on the study by Rudolph et al.[50] Data for each EMG variable were averaged across 5 trials.

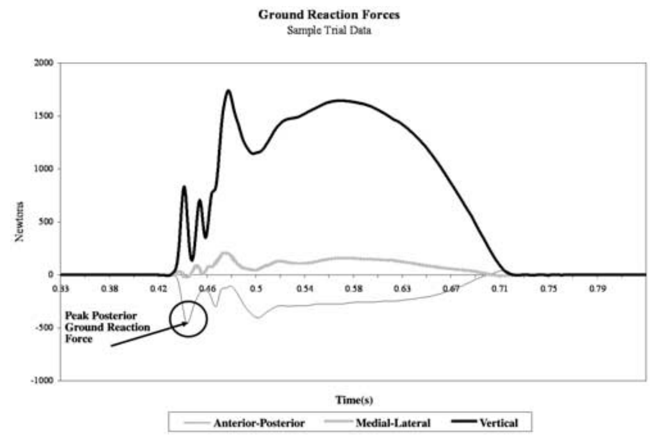

Figure 2. Identification of peak posterior ground-reaction force. AP, Anterior-Posterior; ML, Medial-Lateral.

Data Analysis

All data were analyzed for the right leg only and averaged across 5 trials for each jump condition. Jumps to the left indicate jumps to the medial aspect of the right knee. Jumps to the right indicate jumps to the lateral aspect of the right knee. A 2-way analysis of variance with mixed-factor repeated measures design was analyzed for each of the variables. Jump direction and task (planned or reactive) were treated as the repeated measure. A .05 α level was chosen a priori to denote statistical significance for the analysis of variance. A post hoc Bonferroni multiple comparison test was performed for each variable to determine differences among the jump directions and tasks (planned or reactive). The P values reported for the multiple comparison tests are the Bonferroni-adjusted significance values. In addition to the comparisons across jump direction and between jump tasks, all variables were analyzed with independent t tests to examine potential gender differences during the reactive jumps and the jumps to the left. A .05 α level was chosen a priori to denote statistical significance for these comparisons.

RESULTS

Ensemble means across jump direction and between tasks for knee flexion angle, knee valgus-varus angle, proximal anterior tibia shear force, knee flexion-extension moment, and knee valgus-varus moment are represented in Figures 3 through 7, respectively.

Jump Direction

Jump direction significantly affected joint angles, ground-reaction forces, knee joint moments, and proximal anterior tibia shear forces during the stop-jump tasks. Means and standard deviations for all variables are listed in Table 1. Knee flexion angle at PPGRF and maximum knee flexion angle were significantly different among each of the jump directions ($P < .001$). Jumping to the left had the smallest

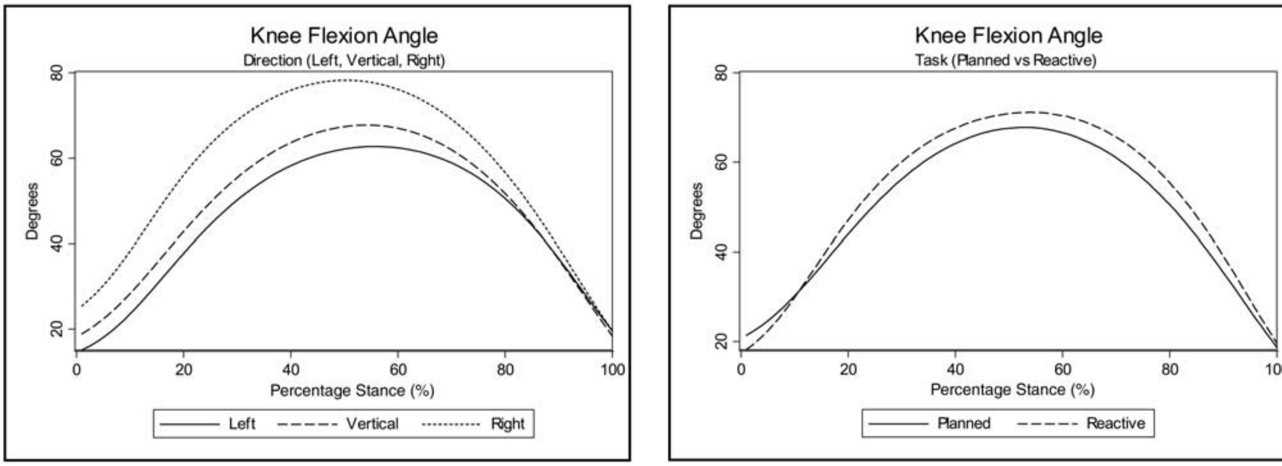

Figure 3. Ensemble mean for knee flexion angle across jump direction and between tasks.

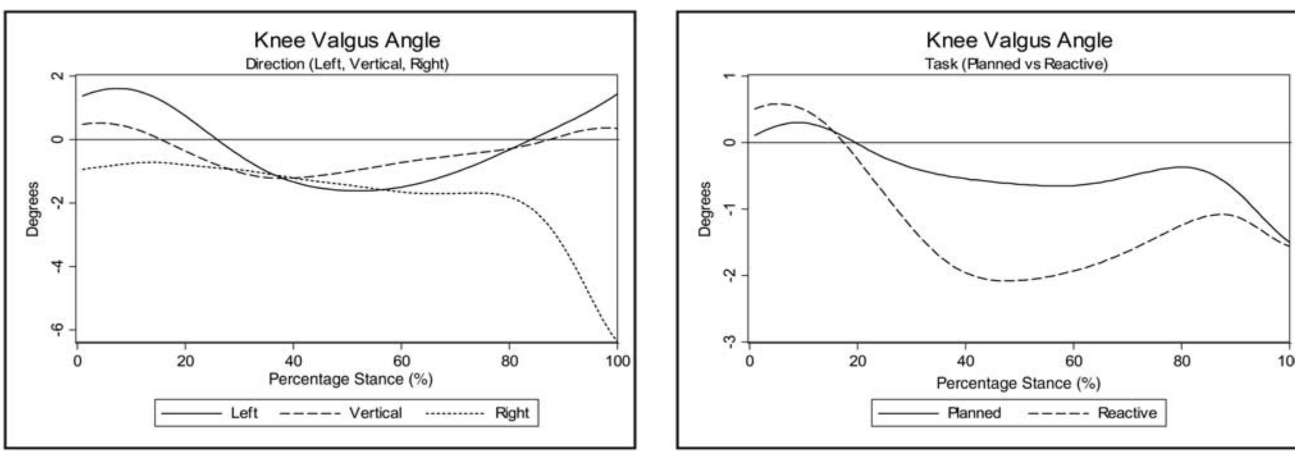

Figure 4. Ensemble mean for knee valgus-varus angle across jump direction and between tasks. A negative value represents a valgus angle.

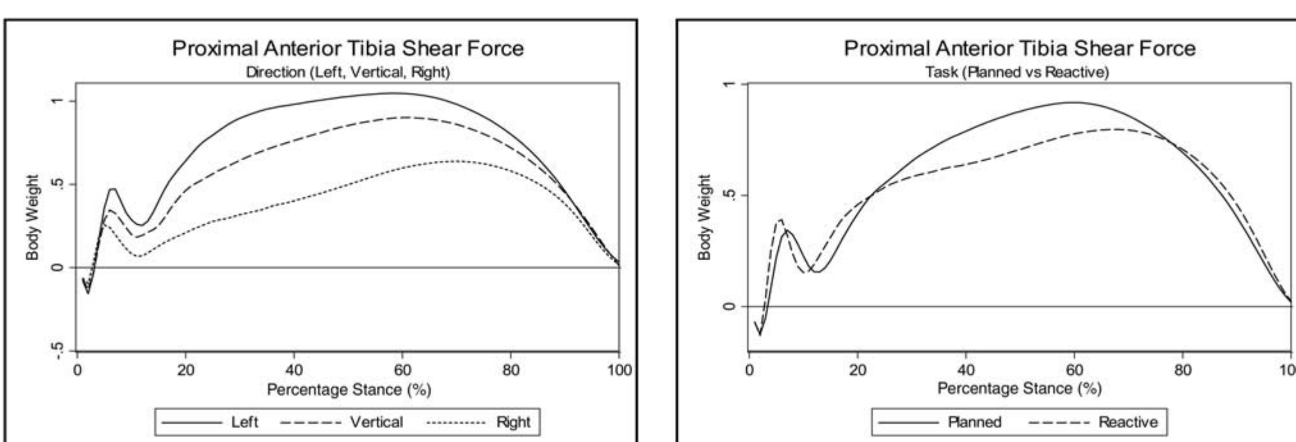

Figure 5. Ensemble mean for proximal anterior tibia shear force across jump direction and between tasks. A positive value represents an internal anterior shear force.

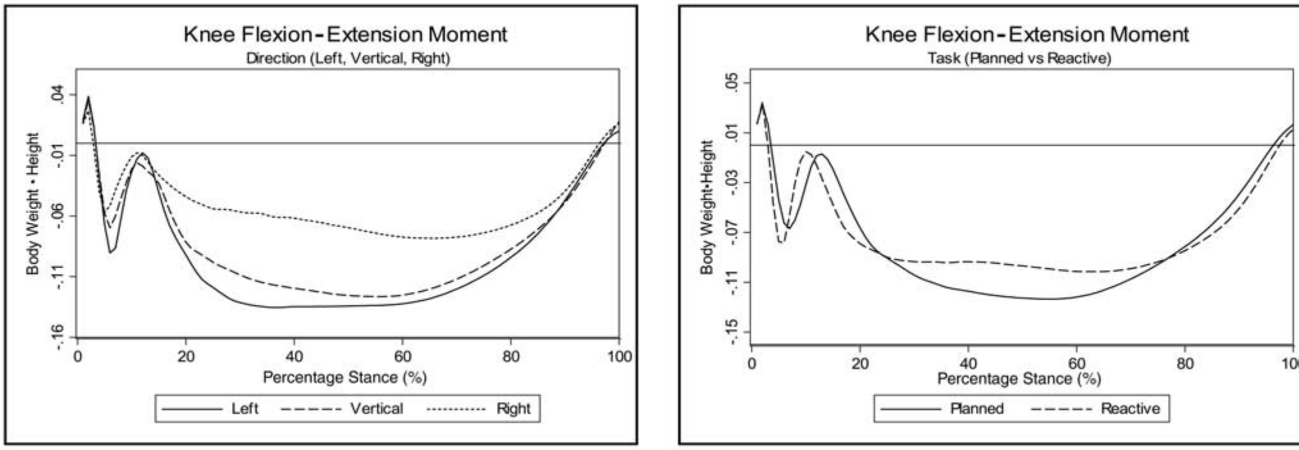

Figure 6. Ensemble mean for knee flexion-extension moment across jump direction and between tasks. A negative value represents an internal quadriceps moment.

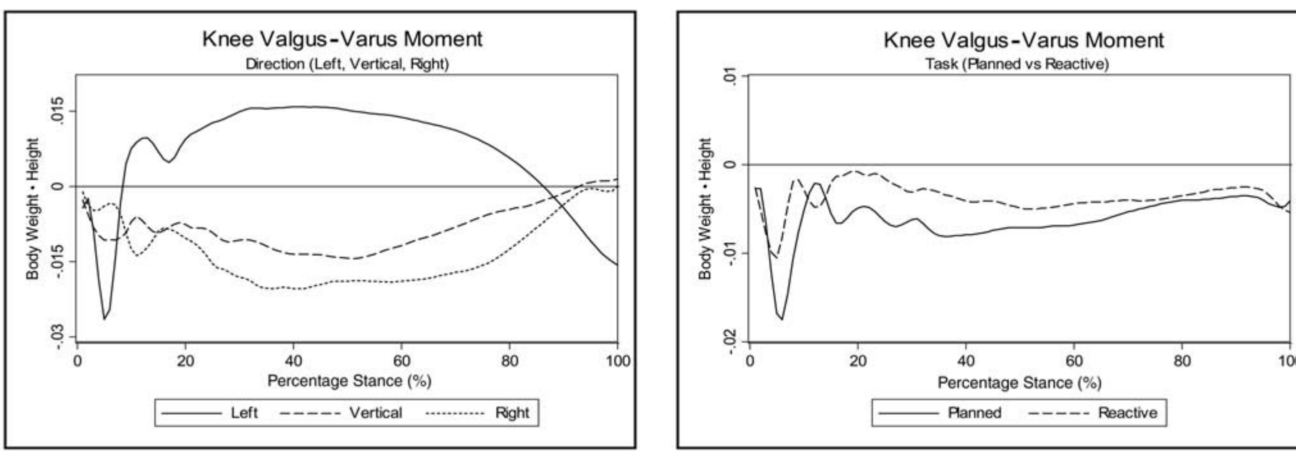

Figure 7. Ensemble mean for knee valgus-varus moment across jump direction and between tasks. A negative value represents an internal varus moment.

maximum flexion angle and was significantly less than jumping vertically ($P = .003$) or to the right ($P < .001$). The maximum knee flexion angle was also significantly smaller in the vertical jumps compared with the jumps to the right ($P < .001$). Knee flexion angle at PPGRF was also significantly less when jumping to the left compared with the vertical jumps ($P = .007$) and jumps to the right ($P < .001$). Subjects also had significantly less knee flexion at PPGRF during the vertical jumps compared with the jumps to the right ($P < .001$). Jumping to the right also demonstrated a significantly greater ($P = .008$) maximum valgus angle compared with the vertical jumps ($P = .022$) and the jumps to the left ($P = .021$).

Both the vertical ground-reaction forces and PPGRF were significantly different across jump directions and between all jump directions ($P < .001$). Jumps to the left had the greatest vertical and posterior ground-reaction forces compared with the vertical jumps and the jumps to the right ($P < .001$). The vertical jumps had significantly greater vertical and posterior ground-reaction forces than the jumps to the right ($P < .001$).

Maximum proximal anterior tibia shear force and proximal anterior tibia shear force at PPGRF were significantly different across jump directions ($P < .001$). Jumping to the left showed significantly greater maximum shear force at PPGRF compared with jumping vertically ($P = .017$) or jumping to the right ($P < .001$). The maximum shear force during the jumps to the left was significantly greater than during the vertical jumps ($P < .001$) and the jumps to the right ($P < .001$). In addition, the maximum shear force during the vertical jumps was significantly greater ($P < .001$) than during those to the right.

The subjects demonstrated significant differences in maximum knee flexion moment ($P < .001$) and knee valgus moment at PPGRF ($P = .0109$) across jump direction. For maximum knee flexion moment, jumping to the left was significantly greater than jumping to the right ($P < .001$). In addition, the subjects performing the vertical jumps

TABLE 1
Comparisons Across Jump Direction[a]

	Left		Vertical		Right	
	Mean	SD	Mean	SD	Mean	SD
Knee flexion angle at PPGRF, degrees[b,c,d]	20.7	7.0	25.8	8.6	34.5	13.1
Maximum knee flexion angle, degrees[b,c,d]	62.9	9.8	68.5	11.5	78.9	8.7
Knee valgus angle at PPGRF, degrees	1.7	5.3	0.4	5.5	–0.7	6.9
Maximum knee valgus angle, degrees[c,d]	–3.9	9.6	–3.9	8.9	–8.0	7.9
Maximum vertical ground-reaction force, body weight[b,c,d]	2.92	0.83	2.25	0.63	1.45	0.45
Maximum posterior ground-reaction force, body weight[b,c,d]	–0.94	0.23	–0.77	0.23	–0.56	0.21
Proximal anterior tibia shear force at PPGRF, body weight[c,d]	0.38	0.19	0.29	0.21	0.24	0.12
Maximum proximal anterior shear force, body weight[b,c,d]	1.11	0.18	1.00	0.18	0.75	0.15
Knee flexion moment at PPGRF, body weight•height	–0.052	0.050	–0.045	0.048	–0.045	0.026
Maximum knee flexion moment, body weight•height[c,d]	–0.176	0.034	–0.167	0.039	–0.127	0.038
Knee valgus moment at PPGRF, body weight•height[c]	–0.022	0.034	–0.014	0.016	–0.007	0.018
Maximum knee valgus moment, body weight•height	–0.051	0.025	–0.045	0.018	–0.044	0.147
Vastus lateralis IEMG	0.139	0.412	0.088	0.066	0.072	0.057
Semitendinosus IEMG	0.081	0.112	0.068	0.065	0.068	0.111
Cocontraction value	0.089	0.073	0.089	0.096	0.064	0.055

[a]PPGRF, peak posterior ground-reaction force; IEMG, integrated electromyogram.
[b]Left significantly different from vertical ($P < .05$).
[c]Left significantly different from right ($P < .05$).
[d]Vertical significantly different from right ($P < .05$).

TABLE 2
Comparison Between Jump Tasks (Planned Versus Reactive)[a]

	Planned		Reactive	
	Mean	SD	Mean	SD
Knee flexion angle at PPGRF, degrees[b]	29.5	11.8	24.4	10.4
Maximum knee flexion angle, degrees[b]	68.6	12.8	71.7	11.0
Knee valgus angle at PPGRF, degrees	0.4	6.4	0.5	5.6
Maximum knee valgus angle, degrees	–4.7	8.7	–5.8	9.3
Maximum vertical ground-reaction force, body weight	2.23	0.90	2.18	0.88
Maximum posterior ground-reaction force, body weight[b]	–0.70	0.24	–0.81	0.29
Proximal anterior tibia shear force at PPGRF, body weight	0.318	0.198	0.283	0.171
Maximum proximal anterior shear force, body weight	0.97	0.23	0.93	0.23
Knee flexion moment at PPGRF, body weight•height[b]	–0.040	0.045	–0.054	0.039
Maximum knee flexion moment, body weight•height	–0.152	0.037	–0.161	0.047
Knee valgus moment at PPGRF, body weight•height	–0.017	0.025	–0.013	0.025
Maximum knee valgus moment, body weight•height[b]	–0.044	0.019	–0.050	0.020
Vastus lateralis IEMG	0.122	0.338	0.076	0.054
Semitendinosus IEMG	0.077	0.099	0.068	0.097
Cocontraction value	0.088	0.089	0.073	0.063

[a]PPGRF, peak posterior ground-reaction force; IEMG, integrated electromyogram.
[b]Significant difference observed between tasks ($P < .05$).

had significantly greater maximum knee flexion moment than those jumping to the right ($P < .001$). For knee valgus moment at PPGRF, the subjects jumping to the left demonstrated greater valgus moment than those jumping to the right ($P = .001$).

Planned Versus Reactive Task

The type of task (planned or reactive) significantly affected joint angles, ground-reaction forces, and knee joint moments. Means and standard deviations for all variables are listed in Table 2. Knee flexion at PPGRF was significantly less in the reactive jumps ($P < .001$), but the maximum flexion angle was significantly greater ($P = .010$). The subjects also had significantly greater PPGRF during the reactive jumps compared with the planned jumps ($P < .001$). The subjects demonstrated significant differences between jump tasks in both knee flexion moment at PPGRF ($P = .022$) and maximum knee valgus moment ($P = .027$). Knee flexion moment at PPGRF was signifi-

TABLE 3
Reactive Task—Male Subjects Versus Female Subjects[a]

	Males		Females	
	Mean	SD	Mean	SD
Knee flexion angle at PPGRF, degrees	24.9	10.2	23.8	10.7
Maximum knee flexion angle, degrees[b]	74.9	9.8	68.4	11.3
Knee valgus angle at PPGRF, degrees	0.3	5.7	–1.4	5.3
Maximum knee valgus angle, degrees[b]	–4.2	7.0	–7.5	10.9
Maximum vertical ground-reaction force, body weight	2.26	0.96	2.11	0.78
Maximum posterior ground-reaction force, body weight	–0.87	0.33	–0.76	0.23
Proximal anterior shear force at PPGRF, body weight[b]	0.26	0.17	0.31	0.17
Maximum proximal anterior shear force, body weight	0.96	0.22	0.94	0.23
Knee flexion moment at PPGRF, body weight•height[b]	–0.033	0.053	–0.048	0.034
Maximum knee flexion moment, body weight•height	–0.170	0.050	–0.153	0.042
Knee valgus moment at PPGRF, body weight•height	–0.009	0.026	–0.016	0.022
Maximum knee valgus moment, body weight•height	–0.046	0.021	–0.041	0.018
Vastus lateralis IEMG	0.068	0.048	0.084	0.059
Semitendinosus IEMG[b]	0.047	0.046	0.090	0.128
Cocontraction value[b]	0.058	0.055	0.088	0.067

[a]PPGRF, peak posterior ground-reaction force; IEMG, integrated electromyogram.
[b]Significant difference observed between genders.

TABLE 4
Jumps to the Left—Male Subjects Versus Female Subjects[a]

	Males		Females	
	Mean	SD	Mean	SD
Knee flexion angle at PPGRF, degrees[b]	22.7	6.4	18.5	7.0
Maximum knee flexion angle, degrees[b]	65.7	9.5	60.0	9.4
Knee valgus angle at PPGRF, degrees[b]	0.5	5.7	–2.9	4.7
Maximum knee valgus angle, degrees	–2.3	7.3	–5.4	11.3
Maximum vertical ground-reaction force, body weight	2.96	1.05	2.88	0.52
Maximum posterior ground-reaction force, body weight	–0.96	0.27	–0.91	0.17
Proximal anterior shear force at PPGRF, body weight	0.36	0.17	0.39	0.22
Maximum proximal anterior shear force, body weight	1.10	0.17	1.12	0.19
Knee flexion moment at PPGRF, body weight•height	–0.047	0.058	–0.058	0.041
Maximum knee flexion moment, body weight•height	–0.177	0.037	–0.175	0.031
Knee valgus moment at PPGRF, body weight•height	–0.106	0.038	–0.029	0.028
Maximum knee valgus moment, body weight•height	–0.052	0.026	–0.050	0.024
Vastus lateralis IEMG	0.083	0.052	0.197	0.588
Semitendinosus IEMG[b]	0.055	0.048	0.108	0.148
Cocontraction value[b]	0.071	0.050	0.108	0.089

[a]PPGRF, peak posterior ground-reaction force; IEMG, integrated electromyogram.
[b]Significant difference observed between genders.

cantly greater in the reactive tasks compared with the planned tasks, and maximum knee valgus moment was also greater in the reactive tasks compared with the planned tasks.

Gender Comparisons

There were significant differences between genders during the reactive tasks and the jumps to the left. The gender means and standard deviations for all variables during the reactive tasks and jumps to the left are presented in Table 3 and Table 4, respectively. Female subjects performed the reactive jumps with significantly less maximum knee flexion (P = .001), a greater maximum valgus angle (P = .0361), greater shear force at PPGRF (P = .0481), and greater knee flexion moment at PPGRF (P = .0436). Female subjects also demonstrated a significantly greater semitendinosus IEMG (P = .0128) and cocontraction value (P = .006) during the reactive jumps. During the jumps to the left, female subjects demonstrated significantly less knee flexion at PPGRF (P = .006), less maximum knee flexion (P = .007), and greater knee valgus at PPGRF (P = .0296). Female subjects also demonstrated a significantly greater semitendinosus IEMG (P = .0226) and cocontraction value ($P = .018$) during the jumps to the left.

DISCUSSION

The purposes of this study were to examine the neuromuscular and biomechanical characteristics during jumping and landing tasks similar to those tasks that have been implicated in noncontact ACL injuries and determine if these same tasks would be performed differently between planned and reactive conditions. The significant findings in this study are that jump direction, task (planned or reactive), and gender had significant effects on the biomechanical characteristics of the knee during the stop-jump movements. Lateral jumps to the medial aspect of the right knee (to the subject's left) were the most dangerous of the 3 jump directions studied, based on the higher ground-reaction forces,[15] proximal anterior tibia shear forces,[33,51] greater valgus and flexion moments,[2,33] and lower flexion angles.[16,33-35,51] Subjects performed the reactive stop-jumps with greater posterior ground-reaction forces, less knee flexion at PPGRF, and greater flexion and valgus moments, indicating potential differences between planned laboratory experiments and actual athletic competition. The gender comparisons revealed that female subjects perform the reactive tasks and the lateral jumps to the left differently from male subjects, indicating different functional joint stabilization strategies.

Jump Direction

Jump direction had a significant effect on the biomechanical characteristics of the knee. Jumps to the medial aspect of the right knee (to the subject's left) had the greatest vertical and posterior ground-reaction forces, greatest proximal anterior tibia shear force, highest valgus and flexion moments, and lowest flexion angles. Although there are many studies that have examined athletic tasks that include a change in direction, only 2 studies compared biomechanical characteristics across different directional movements.[5,10] Besier et al[5] examined the external loading of the knee joint during running and cutting at 30° and 60°. Comparisons between the 2 studies are limited because of the different movements studied, but significant differences were observed in knee flexion moments, ground-reactions forces, and knee flexion angles among the different tasks. Chappell et al[10] examined stop-jump tasks performed in 3 different directions: vertical, forward, and backward. They did not study lateral movements, but they did demonstrate significant differences in anterior tibia shear force, knee flexion moment, and knee valgus moment, based on jump direction.

The results of the comparisons across jump direction seem to support the previous research describing the mechanism of injury.[6,45] The analyses revealed that most of the injuries occur during landing maneuvers that include a change in direction. These mechanisms of injury typically include a valgus collapse of the knee with a landing at a low knee flexion angle. Based on the data collected in this study, jumping to the medial aspect of the right knee (left) seems to be the most dangerous of the movements. This movement is similar to the "plant-and-cut faking movement" described by Olsen et al,[45] which is 1 of 2 common mechanisms of ACL injury that they described. It had the lowest flexion angle, the greatest valgus moment, highest vertical and posterior ground-reaction forces, and the greatest proximal anterior tibia shear force. These biomechanical characteristics can potentially increase the strain in the ACL.[2,15,16,33-35,51]

However, the relationship between ACL strain and external 3D knee joint loading during jump landing movements remains unclear. Previous cadaveric studies have demonstrated that ACL strain is increased as the knee flexion angle is decreased.[16,33-35,51] The mean knee flexion angle when jumping to the left was nearly 14° less than when jumping to the right and 5° less than the vertical jumps. Valgus moment was also significantly greater when jumping to the left. Both Arms et al[2] and Markolf et al[33] have demonstrated that the addition of a valgus moment can increase strain in the ACL when combined with a straight anterior tibial force. Although it is well known that a straight anterior tibial force is the most direct loading mechanism of the ACL,[33,51] it is not clear how proximal anterior tibia force measured through inverse dynamics affects ACL strain. Only one study has examined ACL strain during a dynamic movement similar to those implicated in noncontact ACL injuries.[8] Unfortunately, the researchers did not measure proximal anterior tibia shear force and were unable to correlate this force with the measured ACL strain.

Planned Versus Reactive Task

The subjects used less knee flexion at PPGRF, a greater maximum knee flexion angle, and experienced greater deceleration forces, knee flexion moments, and knee valgus moments during the reactive tasks. The differences observed between the 2 conditions may indicate that knee kinematics and kinetic characteristics are different during actual game situations. Currently, there is very little research examining sports movements during unanticipated maneuvers.[4,18,46] Both Pollard et al[46] and Ford et al[18] have demonstrated gender differences in lower extremity kinematics during unanticipated cutting. Unfortunately, neither research group presented comparisons between planned and unanticipated tasks. Besier et al[4] did make comparisons between these 2 conditions and demonstrated that subjects performed reactive tasks with greater knee joint loading, which was represented in greater knee valgus-varus and internal-external rotation moments. Their subjects also used greater knee flexion (angle) in some unanticipated tasks. They hypothesized that during unanticipated events, athletes make inappropriate postural adjustments, which can increase the knee joint loading characteristics.

In the current study, subjects also demonstrated increased knee joint loading characteristics, as observed in the greater knee valgus and flexion moments. In contrast to Besier et al,[4] our subjects had an increased maximum knee flexion angle during the reactive tasks, but the knee flexion angle at the time of PPGRF, which occurred near footstrike, was significantly less. It is at footstrike that investigators believe ACL injuries typically occur.[6,38,45] Subjects in the current study also demonstrated greater deceleration forces, which can increase the joint loading forces and increase the chance of injury.[15] These increased forces, combined with the increased knee valgus moment[2,33] and decreased knee flexion angle at initial contact,[16,33-35,51] can increase the strain in the ACL. The differences observed between the planned and reactive tasks may indicate that studies that have been performed primarily under planned conditions may underestimate knee joint loading characteristics that can lead to increased ACL strain.

Gender Comparisons

The results of the comparisons between male and female subjects performing the stop-jump tasks indicate that women perform both reactive jumps and jumps to the left in a manner that may increase their ACL strain. The female subjects in this study performed the reactive jumps and jumps to the left with less knee flexion than did their male counterparts. This finding is similar to the results of previous studies examining planned tasks[12,17,30,31,37] but is different from the results of those studies that have examined unplanned tasks during which no differences were observed in knee flexion angle.[18,46] The decreased knee flexion angle observed in the current study may lead to an increase in ACL strain while performing these tasks.[16,33-35,51] An increased knee valgus angle was also observed in the female subjects performing the reactive jumps and the jumps to the left. This finding is also similar to that of previous research examining both planned[17,31,37] and unplanned tasks.[18] These researchers have demonstrated that female subjects perform cutting and landing activities with greater knee valgus than do their male counterparts. It is important that Hewett et al[21] have demonstrated that valgus knee motion is an epidemiological risk factor for noncontact ACL injuries in high school–aged female athletes. In addition to the kinematic differences observed between male and female subjects, significant differences were also observed between genders during the reactive jumps in the proximal anterior tibia shear force at the time of PPGRF. Chappell et al[10] also observed greater proximal anterior tibia shear force in female athletes when performing stop-jump tasks. This increased shear force may increase the anterior tibial translation and place greater strain on the ACL.[33-35]

Finally, a significantly greater semitendinosus IEMG activity and cocontraction value (vastus lateralis to semitendinosus) was observed in female subjects during both the reactive jumps and the jumps to the left. Although previous research examining quadriceps and hamstrings EMG activity of female athletes while performing sports tasks may contradict these results,[11,25,31] our research previously demonstrated similar hamstring activation patterns in female athletes performing a jumping activity.[48] As Rozzi et al[48] described, this finding may reflect a compensatory mechanism to counter the increased knee joint laxity and diminished knee joint proprioception to achieve functional joint stabilization. The increased cocontraction value in the current study is similar to that observed in ACL-deficient persons who were classified as noncopers[49] and those performing unplanned cutting maneuvers,[3] which may indicate a compensatory strategy by female athletes to achieve functional joint stabilization during both the reactive jumps and the jumps to the left.

ACL Injury Prevention

With the increased attention placed on the prevention of noncontact ACL injuries and the increased intensity of studies examining the potential risk factors for these injuries, it is important to use tasks that replicate those movements that have been implicated in noncontact ACL injuries. The current study used a task that incorporated many of the components of these movements: a sharp deceleration, change in direction, and a landing maneuver. By understanding the neuromuscular and biomechanical characteristics of the knee during these tasks, in particular the lateral movements, we may better be able to design projects to investigate the risk factors for noncontact ACL injuries and to design protocols that may be better able to reduce the risk for ACL injuries in female athletes.

The reactive tasks used in this study demonstrated significant differences compared with the planned tasks, which may indicate that the movement strategies observed during planned, controlled laboratory testing are not the same as those observed during athletic competition that typically require moment-to-moment reactions to changing playing conditions. The differences observed during these tasks underscore the importance of including reactive tasks within ACL injury-prevention training protocols, the effects of training on neuromuscular and biomechanical characteristics, research studies examining the differences between male and female athletes, and prospective studies examining the risk factors for noncontact ACL injuries.

Limitations

We collected EMG activity on only the vastus lateralis and semitendinosus muscles, limiting our ability to make conclusions on the effect of this musculature on frontal plane movements. Future research should include EMG analysis on additional knee musculature to determine muscle activation strategies in response to knee moments and forces. The accuracy of skin-based marker systems in estimating joint kinematics and joint kinetics has been questioned during gait.[23,29,32,47] Although we gave careful consideration and attention to marker attachment, the errors caused by skin movement that have been reported during gait may be increased during the high-speed athletic tasks examined in this study. In theory, the markers attached to wands may further exacerbate these errors. A final potential limitation to this study is that only the right leg was examined. The decision to analyze only the right leg was based on an analysis of the vertical jumps, which demonstrated that bilateral differences are present in some variables, but that these differences are not based on right leg, left leg, or the dominant leg (whether it is defined by hand dominance, preferred jumping leg, or preferred kicking leg). We also examined the literature and have not found a relationship between dominance and ACL injury.[21,36]

CONCLUSION

Direction significantly affected the biomechanical characteristics of the knee during the stop-jump tasks that simulated tasks during which noncontact ACL injuries have been reported to occur. Specifically, jumps to the medial aspect are the most dangerous. The reactive component included in this study also altered both joint kinematics and joint loading in a fashion that may increase ACL strain. The female subjects in this study performed the reactive jumps and a jump task designed to simulate a task that has been implicated in noncontact ACL injuries differently from the male subjects. These differences provide evidence for different neuromuscular control strategies. Future research should incorporate both a reactive and a directional component to determine the risk factors for ACL injury and the appropriate intervention strategies to reduce the incidence of noncontact ACL injuries.

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