

Original article

The effect of performance demands on lower extremity biomechanics during landing and cutting tasks

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Abstract

Background: Anterior cruciate ligament (ACL) injuries commonly occur during the early phase of landing and cutting tasks that involve sudden decelerations. The purpose of this study was to investigate the effects of jump height and jump speed on lower extremity biomechanics during a stop-jump task and the effect of cutting speed on lower extremity biomechanics during a side-cutting task.

Methods: Thirty-six recreational athletes performed a stop-jump task under 3 conditions: jumping fast, jumping for maximum height, and jumping for 60% of maximum height. Participants also performed a side-cutting task under 2 conditions: cutting at maximum speed and cutting at 60% of maximum speed. Three-dimensional kinematic and kinetic data were collected.

Results: The jumping fast condition resulted in increased peak posterior ground reaction force (PPGRF), knee extension moment at PPGRF, and knee joint stiffness and decreased knee flexion angle compared with the jumping for maximum height condition. The jumping for 60% of maximum height condition resulted in decreased knee flexion angle compared with the jumping for maximum height condition. Participants demonstrated greater PPGRF, knee extension moment at PPGRF, knee valgus angle and varus moment at PPGRF, knee joint stiffness, and knee flexion angle during the cutting at maximum speed condition compared with the cutting at 60% maximum speed condition.

Conclusion: Performing jump landing at an increased jump speed resulted in lower extremity movement patterns that have been previously associated with an increase in ACL loading. Cutting speed also affected lower extremity biomechanics. Jump speed and cutting speed need to be considered when designing ACL injury risk screening and injury prevention programs.

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Keywords: ACL injury; Injury prevention; Kinematics; Kinetics; Loading mechanism; Risk factor

1. Introduction

Anterior cruciate ligament (ACL) injuries are common sports-related knee injuries. The annual incidence rate of ACL injury is approximately one in every 3000 citizens.^{1,2} ACL injuries not only bring financial burden to the health service³ but also cause devastating consequences to patients' quality of life and can lead to secondary injuries and disorders.^{4,5} Understanding ACL injury mechanisms is crucial for developing evidence-

based injury prevention strategies.^{6,7} Previously, investigators have shown that certain movement patterns such as decreased knee flexion angle, increased impact ground reaction force (GRF), and increased internal knee extension moment are associated with increased ACL loading.^{7–11} Knee valgus/varus angle and valgus/varus moment may also load the ACL when an anterior shear force is applied to the proximal tibia at a small knee flexion angle.^{9,12} In addition, ACL injuries typically occur during the early phase of landing and cutting tasks that involve sudden decelerations.^{13–17} Furthermore, investigators recently quantified knee kinematics near the time of ACL injury based on tibiofemoral bone bruises and found that the knee was close to full extension near the time of injury.¹⁸ Therefore,

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investigators have assessed lower extremity biomechanics associated with ACL loading during jump landing, cutting, and a combination of landing and cutting tasks that simulate the maneuvers that are believed to cause ACL injuries.^{19–25}

During competitive situations, athletic tasks may be performed with different performance demands. For example, a jump task may be performed for maximum jump height or speed for different competitive situations.²⁶ For the same reason, a cutting task may be performed with different cutting speeds. Although performance demand is an important component in the completion of an athletic task, the effect of the performance demand on the lower extremity biomechanics that have been previously associated with ACL injury remains largely unknown. Previously, investigators have focused on the effect of drop height on landing biomechanics and found that impact GRF generally increase as the drop height increases.^{27,28} Although jump-landing biomechanics have been commonly assessed with maximum jump height as the performance demand,^{10,19–21,29–31} it is unknown whether increasing jump height can alter landing mechanics in a way that would increase the risk of an ACL injury. Impact GRF may increase when individuals jump at an increased speed,³² but the effect of jump speed on knee kinematics and kinetics is unclear. In addition, individuals have been commonly assessed using a controlled speed during cutting tasks without clear understanding of how cutting speed may affect lower extremity biomechanics.^{23,33,34} Screening and training athletes without knowing whether the task demand is associated with ACL loading may result in misinterpretation of screening results and mislead injury prevention programs.

As such, the purpose of the current study was to investigate the effects of jump height and jump speed on lower extremity biomechanics during a stop-jump task and the effect of cutting speed on lower extremity biomechanics during a side-cutting task. We hypothesized that increasing jump speed and increasing jump height when performing a stop-jump task would result in increased peak posterior GRF (PPGRF), internal knee extension moment, knee joint stiffness, knee valgus angle, knee varus moment, and decreased knee flexion angle. We further hypothesized that increasing cutting speed when performing a side-cutting task would result in increased PPGRF, internal knee extension moment, knee joint stiffness, knee valgus angle, knee varus moment, and decreased knee flexion angle.

2. Methods

2.1. Participants

Based on previous studies on the effect of drop height and jump-landing technique on lower extremity biomechanics,^{32,35–37} a medium to large effect size was expected for the current study. Assuming an effect size of 0.5 for a pairwise comparison, a sample size of 34 was needed for a type I error of 0.05 and a power of 0.8. Eighteen male and 18 female recreational athletes (age: 22.3 ± 3.3 years; height: 1.74 ± 0.09 m; body mass: 70.9 ± 9.8 kg) who had experience in playing sports that involved landing and cutting tasks participated in the current study. The exclusion criteria included (1) having a lower extrem-

ity injury that prevented participation in physical activity for more than 2 weeks over the previous 6 months; (2) having a history of an ACL injury or other major lower extremity injuries; (3) possessing any condition that prevented maximal participation effort in sporting activities; or (4) pregnancy.³⁸ This study was approved by the University of North Carolina at Chapel Hill Institutional Review Board. Participants signed informed consent forms prior to participation.

2.2. Protocol

Participants performed a vertical stop-jump task for 3 experimental conditions: (1) jumping for maximum height, (2) jumping fast, and (3) jumping for 60% of maximum height. The vertical stop-jump task consists of an approach run followed by a 1-footed takeoff, a 2-footed landing on 2 force plates, and a 2-footed takeoff.^{24,30} During the jumping for maximum height condition, participants were instructed to jump as high as possible following the 2-footed takeoff. During the jumping fast condition, participants were instructed to jump as fast as possible during the 2-footed landing while still trying to jump as high as possible following the 2-footed takeoff. During the jumping for 60% of maximum height condition, participants jumped for 60% of maximum height following the 2-footed takeoff. In our pilot study, we observed that 60% of maximum height gave a general representation of jumping with decreased jump height while participants still maintained a fluid jumping motion. For this condition, participants' maximum jump height was first measured using a Vertec (Sports Imports, Hilliard, OH, USA), and 60% of maximum height was calculated and corresponded to a certain height of the Vertec. Participants practiced 60% of maximum height until they felt comfortable that they could consistently jump to the targeted height. Participants used a single-hand contact technique with the Vertec during both evaluation trials for maximum jump height and practice trials for 60% of maximum height. The Vertec was then removed to be consistent with other jumping conditions, and participants were instructed to maintain 60% of maximum jump height during the jumping for 60% of maximum height condition. The actual jump height was not monitored during data collection but was calculated during data processing based on marker coordinate data.

Participants also performed a side-cutting task with the dominant leg (self-reported preferred leg to jump for distance) for 2 experimental conditions: (1) cutting at maximum speed and (2) cutting at 60% of maximum speed. The side-cutting task consisted of an approach run followed by a 1-footed landing on a force plate and a lateral cut at 45° from the running direction.^{24,39} During the cutting at maximum speed condition, participants were instructed to run as fast as possible and cut as fast as possible. During the cutting at 60% of maximum speed condition, participants cut at 60% of maximum running and cutting speed. For this condition, a regular timer was manually started and stopped by the investigator to quantify the time from the start position to the end position when participants ran and cut as fast as possible. Participants then practiced to complete the task from the same start and end positions using 167% of the total time that was used during the cutting at maximum

speed condition. As such, with the same start and end positions but 167% of the total time, participants were expected to achieve 60% of maximum cutting speed. Participants practiced 60% of maximum cutting speed until they felt comfortable that they could consistently run and cut at the targeted speed. The actual speed was not monitored during data collection but was calculated during data processing based on marker coordinate data.

The order of stop-jump and cutting tasks and the order of different experimental conditions for each task were randomized. A minimum of 5 practice trials were performed before 5 official trials were collected for each experimental condition. Participants had a 3-min rest between experimental conditions and a 30-s rest between trials to reduce the effect of fatigue.

2.3. Data collection

Participants wore Spandex shorts and shirts as well as their own athletic shoes during data collection. Participants performed overground running and self-selected stretching for 5 min to warm-up. Retroreflective markers were attached bilaterally on participants' acromioclavicular joints, anterior superior iliac spines (ASIS), posterior superior iliac spines (PSIS), greater trochanters, lateral and medial femoral condyles, tibial tuberosity, lower shank, lateral and medial malleoli, heels, first and fifth metatarsal heads, and first toes.³⁸ Three-dimensional coordinates of reflective markers were collected using a data acquisition system with 8 Peak Motus video cameras (Peak Performance Technologies, Centennial, CO, USA) at a sampling rate of 120 Hz.^{20,22,24} GRF data were collected using 2 Bertec 4060A force plates (Bertec Corporation, Columbus, OH, USA) at a sampling rate of 1200 Hz.^{19,20,25}

2.4. Data reduction

The data during the landing phase were examined only for the dominant leg. The coordinate and GRF data were filtered using a fourth-order zero-phase-shift low-pass Butterworth filter at a frequency of 10 Hz and 200 Hz, respectively. The cutoff frequency for the coordinate data was estimated using an established method for best accuracy of calculating 2nd time derivatives.⁴⁰ The cutoff frequency for GRF data was obtained from power spectrum analyses of GRFs that demonstrated that most signals of GRFs are below 200 Hz when sampled at 1200 Hz. The use of these cutoff frequencies was consistent with previous studies.^{38,41}

Methods to calculate jump height, approach speed, takeoff speed, and contact time were described in a previous study.³⁸ The center of the pelvis was defined as the center of the left and right ASIS and the left and right PSIS. Jump height was determined by the difference between the maximum vertical coordinates of the center of the pelvis during jumping trials and vertical coordinates of the center of pelvis during static trials. The instantaneous speed of the center of the pelvis at the moments of toe-touch and toe-off was calculated to determine approach and takeoff speed. Contact time was calculated as the total time from toe-touch to toe-off.

Procedures to define joint centers and segment reference frames and methods to calculate joint angles and resultant

moments were consistent with previous studies.^{20,38} The hip joint center was defined as a point in the pelvis reference frame and was located at 19%, 30%, and 14% of the inter-ASIS distance posterior, distal, and medial to the ASIS, respectively.⁴² The knee joint center was defined as the midpoint between the lateral and medial femoral condyles. The ankle joint center was defined as the midpoint between the lateral and medial malleoli. The pelvis reference frame was defined using bilateral ASIS and the middle point of bilateral PSIS. The thigh reference frame was defined using the hip joint center, knee joint center, and lateral femoral condyle. The shank reference frame was defined using the knee joint center, ankle joint center, and lateral femoral condyle. Cardan angles between thigh and shank reference frames were calculated in an order of flexion-extension, varus-valgus, and internal-external rotation.⁴³ Segment masses, center of mass locations, and segment moments of inertia were based on modified Clauser methods.⁴⁴ An inverse dynamics approach was used to calculate lower extremity joint resultant forces and resultant moments.⁴⁵ Joint resultant moments were transferred to the distal segment's reference frame and expressed as internal moments. Joint stiffness was calculated as changes in joint resultant moments divided by changes in joint angles. Forces were normalized to body weight. Moments were normalized to the product of body weight and body height. Data calculations were performed in an MS3D70 computer program package (MotionSoft, Chapel Hill, NC, USA).

For the stop-jump task, performance variables included jump height and contact time. For the side-cutting task, performance variables included approach speed, takeoff speed, and contact time. PPGRF during the early landing phase is considered a critical time point for ACL loading.^{10,20} In addition to PPGRF, knee flexion angle and knee extension moment are important when assessing ACL injury risk.^{6,8-11,18} Knee varus/valgus angle and knee varus/valgus moment may contribute to ACL loading.^{9,12} Therefore, for both stop-jump and side-cutting tasks, kinematic and kinetic variables associated with ACL injury risk included knee flexion angle at initial contact, PPGRF, knee flexion angle at PPGRF, knee extension moment at PPGRF, knee varus/valgus angle at PPGRF, knee varus/valgus moment at PPGRF, peak knee flexion angle, knee flexion range of motion from initial contact to peak flexion, and sagittal plane knee joint stiffness from initial contact to peak flexion.

2.5. Statistical analysis

Performance, kinematic, and kinetic variables were compared among 3 stop-jump conditions using analysis of variance with repeated measures. Only significant analyses of variance were followed by paired *t* tests. Performance, kinematic, and kinetic variables were compared between the 2 side-cutting conditions using paired *t* tests. An outlier was defined as a value that deviated from the mean by more than 3 times the standard deviation and significantly affected the significance level of a statistical test. A type I error rate less than or equal to 0.05 was chosen as indication of statistical significance. The Holm step-down procedure was used to adjust the type I error rate of each

Table 1

Performance outcomes and kinematic and kinetic variables (mean $\pm$ SD) during the 3 stop-jump conditions (jumping fast, jumping for maximum height, and jumping for 60% of maximum jump height).

	Jumping fast	Jumping for max. height	Jumping for 60% of max. height	<i>p</i>		
				Fast vs. max. height	Fast vs. 60% of max. height	Max height vs. 60% of max. height
Jump height (m)	0.38 $\pm$ 0.11	0.48 $\pm$ 0.12	0.31 $\pm$ 0.07	<0.001*	<0.001*	<0.001*
Contact time (ms)	233.0 $\pm$ 34.8	318.3 $\pm$ 62.3	297.5 $\pm$ 48.3	<0.001*	<0.001*	0.066
Knee flexion angle at initial contact (°)	23.5 $\pm$ 8.6	24.9 $\pm$ 7.8	19.2 $\pm$ 7.2	0.117	<0.001*	<0.001*
PPGRF (BW)	-0.87 $\pm$ 0.27	-0.65 $\pm$ 0.26	-0.59 $\pm$ 0.19	<0.001*	<0.001*	0.033
Knee flexion angle at PPGRF (°)	31.5 $\pm$ 7.9	35.1 $\pm$ 7.7	29.6 $\pm$ 6.9	<0.001*	0.041	<0.001*
Knee flexion (+)/extension (-) moment at PPGRF (BW $\times$ BH)	-0.09 $\pm$ 0.04	-0.07 $\pm$ 0.04	-0.06 $\pm$ 0.03	0.006*	<0.001*	0.048
Knee varus (+)/valgus (-) angle at PPGRF (°)	-1.18 $\pm$ 5.50	-0.44 $\pm$ 6.14	-0.68 $\pm$ 5.61	—	—	—
Knee varus (+)/valgus (-) moment at PPGRF (BW $\times$ BH)	-0.005 $\pm$ 0.049	-0.011 $\pm$ 0.033	-0.008 $\pm$ 0.032	—	—	—
Peak knee flexion angle (°)	58.7 $\pm$ 8.6	73.8 $\pm$ 11.0	67.4 $\pm$ 7.6	<0.001*	<0.001*	<0.001*
Knee flexion range of motion (°)	35.1 $\pm$ 7.6	48.9 $\pm$ 9.4	48.2 $\pm$ 8.4	<0.001*	<0.001*	0.681
Knee joint stiffness (BW $\times$ BH/°)	-0.005 $\pm$ 0.001	-0.003 $\pm$ 0.001	-0.003 $\pm$ 0.001	<0.001*	<0.001*	0.315

* Significant *p* values at an adjusted type I error rate.

Abbreviations: BH = body height; BW = body weight; max. = maximum; PPGRF = peak posterior ground reaction force.

paired *t* test to keep the overall type I error rate no greater than 0.05.⁴⁶ Statistical analyses were performed in SPSS 16.0 (SPSS Inc., Chicago, IL, USA).

3. Results

For the stop-jump task, *p* values of analysis of variance were less than 0.001 for jump height, contact time, knee flexion angle at initial contact, PPGRF, knee flexion angle at PPGRF, knee extension moment at PPGRF, peak knee flexion angle, knee flexion range of motion, and knee joint stiffness, but not for knee varus/valgus angle at PPGRF (*p* = 0.294) or knee varus/valgus moment at PPGRF (*p* = 0.470). Paired *t* tests were performed between each pair of jumping conditions for the 9 variables that showed significant analysis of variance (Table 1). For the side-cutting tasks, the knee joint stiffness data of 1 participant were identified as outliers and not included in the analysis. Paired *t* tests were performed between 2 cutting conditions for all 12 variables (Table 2). A total of 39 paired *t* tests were performed for both the stop-jump and side-cutting tasks

(Tables 1 and 2). The largest *p* value for a significant paired *t* test was 0.006 after the adjustment for the overall type I error rate (Table 1).

For the stop-jump task (Table 1), jump height was the greatest during the jumping for maximum height condition, the second greatest during the jumping fast condition, and the least during the jumping for 60% of maximum height condition. The actual jump height during the jumping for 60% of maximum height condition was 65.6% $\pm$ 13.1% (mean $\pm$ SD) of the jump height during the jumping for maximum height condition. Contact time was significantly shorter during the jumping fast condition compared with the other 2 jumping conditions. Knee flexion angle at initial contact was significantly smaller during the jumping for 60% of maximum height condition compared with the other 2 conditions. PPGRF, knee extension moment at PPGRF, and knee joint stiffness were significantly greater during the jumping fast condition compared with the other 2 jumping conditions. Knee flexion angle at PPGRF was significantly greater during the jumping for maximum height condi-

Table 2

Performance outcomes and kinematic and kinetic variables (mean $\pm$ SD) during the 2 side-cutting conditions (cutting at maximum speed and cutting at 60% of maximum speed).

	Cut maximum speed	Cut 60% of maximum speed	<i>p</i>
Approach speed (m/s)	3.8 $\pm$ 0.4	2.1 $\pm$ 0.3	<0.001*
Takeoff speed (m/s)	4.2 $\pm$ 0.4	2.3 $\pm$ 0.3	<0.001*
Contact time (ms)	298.4 $\pm$ 45.1	439.2 $\pm$ 96.1	<0.001*
Knee flexion angle at initial contact (°)	24.0 $\pm$ 6.7	10.6 $\pm$ 6.7	<0.001*
PPGRF (BW)	-0.70 $\pm$ 0.29	-0.28 $\pm$ 0.20	<0.001*
Knee flexion angle at PPGRF (°)	28.0 $\pm$ 5.0	17.3 $\pm$ 6.8	<0.001*
Knee flexion (+)/extension (-) moment at PPGRF (BW $\times$ BH)	-0.06 $\pm$ 0.05	-0.03 $\pm$ 0.03	0.001*
Knee varus (+)/valgus (-) angle at PPGRF (°)	-2.50 $\pm$ 4.90	-0.59 $\pm$ 5.12	<0.001*
Knee varus (+)/valgus (-) moment at PPGRF (BW $\times$ BH)	0.007 $\pm$ 0.042	-0.017 $\pm$ 0.019	<0.001*
Peak knee flexion angle (°)	49.7 $\pm$ 5.9	44.1 $\pm$ 7.3	<0.001*
Knee flexion range of motion (°)	25.7 $\pm$ 8.7	33.5 $\pm$ 8.6	<0.001*
Knee joint stiffness (BW $\times$ BH/°)	-0.007 $\pm$ 0.003	-0.003 $\pm$ 0.001	<0.001*

* Significant *p* values at an adjusted type I error rate.

Abbreviations: BH = body height; BW = body weight; PPGRF = peak posterior ground reaction force.

tion compared with the other 2 conditions. Peak knee flexion angle was the greatest during the jumping for maximum height condition, the second greatest during the jumping for 60% of maximum height condition, and the least during the jumping fast condition. Knee flexion range of motion was significantly smaller during the jumping fast condition compared with the other 2 jumping conditions.

For the side-cutting task (Table 2), participants demonstrated significantly greater approach and takeoff speeds and shorter contact time during the cutting at maximum speed condition compared with the cutting at 60% of maximum speed condition. The actual approach and takeoff speeds during the cutting at 60% of maximum speed condition were $54.9\% \pm 8.5\%$ and $55.5\% \pm 8.2\%$ of those during the cutting at maximum speed condition, respectively. Participants demonstrated significantly greater knee flexion angle at initial contact, PPGRF, knee flexion angle at PPGRF, knee extension moment at PPGRF, knee valgus angle at PPGRF, knee varus moment at PPGRF, peak knee flexion angle, and knee joint stiffness, and decreased knee flexion range of motion during the cutting at maximum speed condition compared with the cutting at 60% of maximum speed condition.

4. Discussion

The purpose of the current study was to investigate the effects of jump height and jump speed on lower extremity biomechanics during a stop-jump task and the effect of cutting speed on lower extremity biomechanics during a side-cutting task. The results of performance outcomes support that participants achieved different performance demands during different jumping and cutting conditions. The performance outcomes during the stop-jump task were consistent with a recent study,²⁶ which has shown that jump height and jump speed are 2 different task demands, and it is unlikely to jump for maximum height and highest speed at the same time. The findings of kinematic and kinetic variables partially support our hypothesis.

The findings of this study support the hypothesis that performing stop jump at an increased speed would result in increased PPGRF, internal knee extension moment, and knee joint stiffness and decreased knee flexion angle. Different from drop-landing and drop-vertical jump tasks,^{19,28,35} the stop-jump task begins with an approach run and involves sudden decelerations in the anterior-posterior direction during landing. To achieve the goal of jumping as fast as possible, participants landed stiffer, as indicated by the decreased knee flexion angle at PPGRF, peak knee flexion angle, and knee flexion range of motion compared with the jumping for maximum height condition. This stiff landing pattern ensured that participants could absorb the approach momentum in a short time and reduce the total contact time. However, PPGRF, knee extension moment at PPGRF, and knee joint stiffness increased as compensation for the decreased contact time. The findings of increased PPGRF are consistent with the study by Walsh et al.,³² who found greater impact GRF when participants landed and jumped with a shorter contact time. Meanwhile, investigators have previously shown decreased impact GRF when participants utilized

a soft landing pattern that is characterized by increased knee flexion angles and contact time, indicating a decreased jump speed.^{38,47} The findings of previous studies and the current study suggest that jump speed is a sensitive factor associated with lower extremity biomechanics during jump landing. On the other hand, jump speed did not result in significant differences in knee valgus angle and knee varus moment at PPGRF, which could be associated with the predominance of sagittal plane motion during the stop-jump task. Performing jump landing at an increased speed may impose a task demand that is associated with increased sagittal plane loading of the ACL.

The findings of this study do not support the hypothesis that jumping for a greater height would result in increased PPGRF, internal knee extension moment, and knee joint stiffness and decreased knee flexion angle. Actually, jumping for maximum height resulted in increased knee flexion angle at initial contact, knee flexion angle at PPGRF, and peak knee flexion angle but similar PPGRF, knee extension moment at PPGRF, knee valgus angle at PPGRF, knee varus moment at PPGRF, knee flexion range of motion, and knee joint stiffness compared with jumping for 60% of maximum height. Previously investigators have focused on the effect of drop height on lower extremity biomechanics during drop-vertical jump tasks.^{27,28} Jump-landing task have been usually completed with participants jumping for maximum jump height.^{10,19–21,29,30} The results of the current study, however, suggest that jumping for 60% of maximum height may represent a scenario that is associated with increased ACL loading compared with jumping for maximum height, because of the decreased knee flexion angle.⁸ The average knee flexion angle at PPGRF during the jumping for 60% of maximum height condition was below 30° , which is considered a critical knee flexion angle associated with greater ACL loading.^{48,49} A low knee flexion angle may amplify ACL loading in combination with other loading mechanisms such as anterior shear force and knee valgus/varus moment.^{9,12} From a mechanical perspective, a decreased jump height indicated that less kinetic energy needed to be generated during the takeoff phase of landing. During the jumping for maximum height condition, it was postulated that participants utilized a self-optimized joint range of motion for maximizing force production during the takeoff. On the other hand, during the jumping for 60% of maximum height condition, participants utilized a decreased knee flexion angle strategy during landing, which corresponded to a joint range of motion associated with less force production during the takeoff. The findings of the current study do not support the belief that increasing jump height may change landing mechanics in a way that would increase the risk of an ACL injury. Assessing jump-landing mechanics with maximum jump height as the performance demand, therefore, may not represent ACL injury scenarios.

The findings of this study support the hypothesis that performing side-cutting at an increased speed would result in increased PPGRF, knee extension moment at PPGRF, and knee joint stiffness and decreased knee flexion range of motion. An increased speed also resulted in an increase in the knee valgus angle at PPGRF and the knee varus moment at PPGRF. The average knee flexion angles at PPGRF during both side-cutting

conditions were less than 30°. However, performing side-cutting at an increased speed also resulted in increased knee flexion angle at initial contact, knee flexion angle at PPGRF, and peak knee flexion angle. Previous investigators have studied the effects of performance demands such as reaction time and fatigue on lower extremity biomechanics during cutting.^{50,51} Participants have been commonly tested with cutting speed as a control variable.^{23,33,34} In the current study, similar to the stop-jump task, participants utilized a movement pattern with decreased knee flexion angle during the cutting with 60% of maximum speed condition. This decrease may be associated with a decreased task demand to produce force and generate kinetic energy. During the cutting with maximum speed condition, participants started with greater knee flexion at initial contact but reduced knee flexion range of motion to reduce the total contact time, and the task demand of great force production within a short contact time resulted in greater PPGRF, knee extension moment at PPGRF, and knee joint stiffness. The findings suggest that cutting speed could significantly modify lower extremity biomechanics and support the notion of controlling cutting speed when assessing cutting mechanics. In addition, performing cutting task at different speeds may pose loads to the ACL from difference mechanisms.

There were several limitations of the current study. We evaluated only jump height and jump speed as performance demands for the stop-jump tasks, and cutting speed was the only performance demand for the side-cutting task. Other task demands, such as the anticipated vs. unanticipated nature of the task, jumping/cutting directions, and fatigue, were not evaluated and could interact with jump height, jump speed, and cutting speed to alter the movement patterns in the lower extremity. Participants practiced the 60% of maximum jump height and 60% of maximum cutting speed conditions before data were collected. Participants' actual jump height and cutting speed during these 2 conditions were calculated using marker coordinates during data processing but were not monitored during data collection owing to software limitations. Differences were observed between the targeted and actual jump height and cutting speed during these 2 conditions. These differences could be caused by different measurement methods (Vertec and regular timer vs. markers) between data collection and data reduction. Participants' variation in maintaining targeted jump height and cutting speed may also contribute to these differences. The purpose of the current study was to compare lower extremity biomechanics between conditions with maximum performance demands and relatively lower performance demands. In addition, the differences between the targeted (60%) and actual jump height (66%) and cutting speed (55%) were only 5%–6%. As such, this discrepancy in jump height and cutting speed may affect the exact magnitudes of dependent variables but should not affect the general changes in dependent variables and the conclusion of the current study. In addition, only 1 decreased jump height condition and 1 decreased cutting speed condition were studied. Real-time monitoring of jump height and cutting speed may improve the consistency in achieving the targeted jump height and cutting speed and allow evaluation of the effect of small incremental

changes in jump height and cutting speed on lower extremity biomechanics. We assessed only lower extremity biomechanics that have been previously shown to be associated with ACL injury. Estimated ACL loading becomes inconclusive when loading variables such as knee flexion angle and knee extension moment change in different directions. Future research to directly measure ACL length or strain could provide a better understanding of changes in ACL loading as a function of different performance demands.

5. Conclusion

Performing jump landing at increased jump speed resulted in lower extremity movement patterns that have been previously associated with an increase in ACL loading. Cutting speed also affected lower extremity biomechanics. Jump speed and cutting speed need to be considered when designing injury risk screening and injury prevention programs. More dynamic tasks with decreased contact time could be used in the development of injury prevention programs during the final stages of training as well as being incorporated into the final stages of rehabilitation as athletes are returned to sport after an injury to insure that they are ready to meet the demands of athletic competition.

Authors' contributions

BD and BY contributed to the design of the study, data collection, data reduction, and data analysis and drafted the manuscript; WEG, MTG, DAP, and RMQ contributed to the design of the study and data analysis and helped to draft the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

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