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Predictors of frontal plane knee moments during side-step cutting to 45° and 110° men and women: Implications for ACL injury

Susan M. Sigward, PhD, **Guilherme M. Cesar, MS**, and **Kathryn L. Havens, PhD**
Human Performance Laboratory, Division of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, California

Abstract

Objective—To compare frontal plane knee moments, and kinematics and kinetics associated with knee valgus moments between cutting to 45° and 110°, and to determine the predictive value of kinematics and ground reaction forces (GRFs) on knee valgus moments when cutting to these angles. Also, to determine whether sex differences exist in kinematics and kinetics when cutting to 45° and 110°.

Design—Cross-sectional study.

Setting—Laboratory setting.

Participants—Forty five (20 females) healthy young adult soccer athletes ages 16-23 years.

Assessment of Risk Factors—Kinematic and kinetic variables were compared between randomly-cued side-step cutting maneuvers to 45° and 110°. Predictors of knee valgus moment were determined for each task.

Main Outcome Measures—Kinematic variables: knee valgus angle, hip abduction and internal rotation angles. Kinetic variables: vertical, posterior, and lateral GRFs, and knee valgus moment.

Results—Knee valgus moments were greater when cutting to 110° compared to 45°, and females exhibited greater moments than males. Vertical and lateral GRFs, hip internal rotation angle, and knee valgus angle explained 63% of the variance in knee valgus moment during cutting to 45°. During cutting to 110°, posterior GRF, hip internal rotation angle, and knee valgus angle explained 41% of the variance in knee valgus moment.

Conclusion—Cutting tasks with larger redirection demands result in greater knee valgus moments. Similar factors including shear GRFs, hip internal rotation and knee valgus position contribute to knee valgus loading during cuts performed to smaller (45°) and larger (110°) angles.

Keywords

Anterior crucial ligament injury; Cutting maneuver; Soccer; Sex differences

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Corresponding author: Susan M. Sigward, PhD University of Southern California 1540 East Alcazar St., CHP-155 Los Angeles, CA 90033 Office: 323-442-2454 Fax: 323-442-1515 gward@usc.edu.

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INTRODUCTION

The incidence of anterior cruciate ligament (ACL) injuries is disproportionately higher in female athletes compared to their male counterparts; females have a 3-5 times higher incidence of non-contact ACL injury.[1-3] Sex-related differences in knee joint mechanics during the performance of athletic tasks are thought to contribute to increased risk for injury in athletes. Specifically, athletes who exhibit larger knee valgus angles,[4,5] knee valgus moments (also reported as external knee abductor or internal knee adductor moments), [6-8] and greater ground reaction forces (GRFs)[9] during landing and cutting tasks are thought to be at increased risk for non-contact ACL injuries. A prospective study found that females who went on to injure their ACL exhibited 8° more knee valgus, 2.5 times greater knee valgus moments, and 20% higher vertical GRF (component of the GRF that counteracts the downward force applied on the ground when the foot contacts the ground) during a landing task than those who did not and knee valgus moments and angles were predictor of injury status.[10]

Up to 70% of non-contact injuries occur during a cutting or change of direction maneuver.[11,12] This is of concern, as soccer athletes perform an average of 726 ±203 cutting maneuvers in a game to angles that vary from 0° to 180°.[13] While biomechanical analyses of cutting have focused primarily on maneuvers performed to smaller degrees (e.g., 45°), a comparison between side-step cutting tasks performed to 30° and 60° suggests that cutting to larger angles results in greater knee loading in male athletes.[14] Less is known regarding cutting task performed to angles greater than 90°. Moreover, it is not known if the same sex differences in knee loading observed when cutting to small angles exist when cutting to larger angles.

Increased knee valgus moments during cutting to 45° have been associated with lower extremity position at initial contact and GRFs.[7,15] Specifically, greater hip internal rotation and abduction, knee valgus angle at contact and peak lateral GRF (component of the GRF that counteracts the medial, or shear force, applied on the ground when the foot contacts the ground) were correlated with larger knee valgus moments in females. Together these variables explained 49% of the variance in knee valgus moment in female athletes during a 45° side-step cutting task.[15] In addition, hip internal rotation and knee valgus angles have been correlated with knee valgus moments for both males and females during a similar cutting task.[7] It is not clear if these same mechanics relate to knee loading when cutting to larger angles. Understanding the postures that contribute to knee loading during cutting to different angles is important for the development of effective injury prevention strategies.

The primary aim of this study was to compare knee valgus moments and the kinematic and GRF variables associated with knee valgus moments between cutting maneuvers performed to 45° and 110°. The secondary aim was to determine the predictive value of lower extremity kinematics and GRFs on knee valgus moments during these tasks. The tertiary aim was to determine whether differences in kinematics and kinetics exist between males and females. We hypothesized that when compared to the 45° cut, athletes will exhibit greater knee valgus moments and GRF’s, as well as larger knee valgus, hip abduction and hip internal rotation angles while cutting to 110°. We also hypothesized that knee valgus moments would be associated with greater knee valgus, hip internal rotation and abduction angles as well as larger lateral GRFs during both cutting tasks. Lastly, we hypothesized that females would exhibit greater knee valgus moments and GRF's, larger knee valgus, hip abduction and hip internal rotation angles when compared to males during both tasks.

METHODS

Participants

Forty five soccer athletes (20 females) between the ages of 16 and 23 years participated (Table 1). All subjects were participating in organized club soccer with similar training schedules that included practice or competition 3 to 5 days a week. Subjects were injury-free at the time of participation. They were excluded from the study if they reported a history of previous ACL injury or repair; previous injury that resulted in ligamentous laxity at the ankle, hip, or knee; or any medical condition that would impair their ability to perform the experimental tasks. To control for influence of maturation [16,17], study participants were considered only if they had completed puberty. Self-report Tanner scale for pubic hair development from figured drawings[18,19] and the modified Pubertal Maturation Observational Scale (PMOS)[20] were used to determine if individuals were post-puberty as described previously.[16]

Procedures

Testing took place at the Human Performance Research Laboratory of the Division of Biokinesiology and Physical Therapy. All procedures were explained to each subject and informed consent obtained as approved by the Health Sciences Institutional Review Board of the University of Southern California. Parental consent and youth assent were obtained for all subjects under the age of 18 years.

Ground reaction force data were obtained using a force platform at 1500 Hz (Model #OR6-61, Advanced Mechanical Technologies, Inc., Newton, Massachusetts). Three-dimensional kinematics were collected using an eight-camera, motion analysis system (Vicon, Oxford Metrics LTD, Oxford, England) at 250 Hz. Reflective markers (10 mm spheres) placed on specific boney landmarks were used to quantify lower extremity and pelvic segment motion as described previously.[16,21] To control for the potential influence of varying footwear, subjects were fitted with same style cross-training shoe (New Balance Inc., Boston, Massachusetts).

For the side-step cutting tasks, subjects ran between 4.5–5.5m/s for 7 meters, planted their dominant foot on the force plate and changed direction to the opposite side. A light cue triggered 3m prior to the force plate indicated that the subjects should perform one of 3 tasks: change of direction at 45° angle (CUT45) or a 110° angle (CUT110) from the initial plane of progression or no cut (i.e., straight run) (Figure 1). Task direction was presented in random order. Subjects performed each cutting task without cueing 4 times and were allowed to practice with the random light cue until they were comfortable with the task. Approach velocity was calculated over 3 meters using of a photoelectric switch and force plate contact. Trials were accepted if the subject's foot landed completely on the force platform at the pre-determined speed, and they cut to the cued angle. Four acceptable trials for each task were recorded.

Data Analysis

Coordinate data were digitized using Vicon Workstation software and filtered using a fourth-order zero-lag Butterworth 12-Hz low-pass filter. Three-dimensional lower extremity kinematics and net joint moments were calculated with Visual3D™ (C-Motion, Inc., Rockville, Maryland) software as described previously.[16] Briefly, local coordinate systems of pelvis, thighs, shanks and feet were derived from the standing calibration trial, and the six degrees of freedom of each segment was determined from the segment's triad of reflective markers. The kinematics were calculated by determining the transformation from the triad of markers to the position and orientation of each segment determined from the standing calibration trial using a joint coordinate system approach.[22] Internal net joint moments were calculated using standard inverse dynamics equations.[23]

Data at initial contact and during the weight acceptance phase of the cutting task were considered for this study. This phase is considered important as it is the period during which the majority of non-contact ACL injuries are thought to occur[11] and is the time during which a peak knee valgus moment is observed. As described in previous studies, weight acceptance phase was determined by the force plate recordings and was defined as the period from initial contact to the first trough of the vertical GRF.[24] The variables of interest included knee valgus, hip abduction and hip internal rotation angles at initial contact; peak knee valgus moment (normalized to body mass and height), and peak vertical, posterior (force that counteracts the anterior force applied on the ground when the foot contacts the ground), and lateral GRFs (normalized to body mass) during weight acceptance. Four trials were averaged per subject and used for statistical analysis.

Statistical Analysis

In order to examine the effects of angle and sex, separate 2×2 analyses of variance (ANOVAs) with repeated measures were performed for each variable of interest. To evaluate if the variables of interest predicted peak knee valgus moment, separate stepwise multiple regression models were used for each cut condition. Peak knee valgus moment was the dependent variable. Knee valgus, hip abduction and internal rotation angles and vertical, posterior, and lateral GRFs were considered the independent variables. All statistical analyses were performed using SPSS statistical software (Chicago, Illinois, v.18), $p < 0.05$.

Although approach velocity was limited to a pre-determined range (4.5–5.5m/s), significant difference in approach velocity was observed between sexes ($p=0.04$). On average, females approach the cutting tasks slower (4.77±0.07m/s) compared to males (4.97±0.06m/s). Significant difference in approach velocity was not observed between cutting angles ($p=0.19$). To avoid the potential influence of approach velocity on group differences in kinetic variables, GRF and moment data were analyzed independent of velocity. For this, a linear regression model was conducted for each kinetic variable. Each variable was entered as dependent variable and approach velocity as the independent variable. The residual obtained from this procedure represents the GRF and moment data without the influence of (i.e., covariate) approach velocity and allows for comparisons between tasks. Therefore, the unstandardized residuals from the regressions were saved and used for sex and angle comparisons.

RESULTS

Knee Valgus Moment

A significant difference in knee valgus moment was observed between sexes and between cutting angles (Table 2). Knee valgus moments were greater during CUT110 (1.23±0.07 N/kg*m; $P < 0.001$;) compared to CUT45 (mean±standard error; 0.51±0.05 N/kg*m; residuals −0.36±0.04). Females exhibited greater knee valgus moments than males (0.96±0.07 N/kg*m versus 0.80±0.07 N/kg*m; $P = 0.02$; residuals 0.12±0.01 versus −0.09±0.01). A trend toward a greater difference between males and females in knee valgus moment was observed during CUT110 compared to CUT45 (Figure 2)

Ground Reaction Forces

All GRF variables were greater in CUT110 compared to CUT45 (Table 2). Differences were noted between males and females in vertical and posterior GRF but not lateral GRF. When considering posterior GRF, females had greater GRF than males during CUT110 but not during CUT45 (Figure 3). A similar trend was observed in vertical GRF (Figure 3).

Kinematics

Significant differences between CUT 45 and CUT110 were observed for hip abduction and internal rotation angle. Greater hip abduction angle (19.04±0.98° versus 4.96±0.86°; $P = 0.01$) and smaller hip internal rotation angle (5.39±1.08° versus 7.76±0.98°; $P = 0.03$) were observed at initial contact during CUT110 compared to CUT45. Significant differences between males and females were observed for knee valgus angle and hip abduction angle. Females exhibited greater knee valgus angle (3.63±0.57° versus 0.97±0.51°; $P = 0.001$) and smaller hip abduction angle (9.90±1.19° versus 14.08±1.07°; $P = 0.01$) at initial contact than males (Table 2).

Predictors of Peak Knee Valgus Moment

For CUT45 vertical GRF entered the regression equation first and was found to be the largest predictor of peak knee valgus moment, followed by lateral GRF, hip internal rotation angle, and knee valgus angle (Table 3). Together these variables explained 62.9% of the variance in knee valgus moment ($F_{4,40}$=19.654 , $P < 0.001$). For CUT110, posterior GRF entered the equation first, followed by hip internal rotation angle, and knee valgus angle (Table 3). Together they explain 41.5% of the variance in peak knee valgus moment ($F_{3,41}$=11.413, $P < 0.001$).

DISCUSSION

This is the first study to investigate knee frontal plane loading during unanticipated cutting to an angle greater than 90°. This is important given that cutting maneuvers performed to greater angles are common in multi-directional sports.[13] Knee valgus moments were 2.4 times greater during the 110° cut compared to the 45° cut. As increased knee valgus moments have been associated with increased risk for ACL injury,[10] these data suggest that ACL injury risk may be higher when performing cutting maneuvers to greater angles. This appears to be particularly true for female athletes. Similar to previous studies,[7,15] larger knee valgus moments and knee valgus angles were observed in females compared to males.

While kinematic and kinetic differences exist between cutting tasks, similarities in predictors suggest that common factors may underlie the mechanism for frontal plane knee loading during cutting. Greater GRFs during CUT110 compared to CUT45 suggest that greater force is required to redirect the body to a larger angle. More specifically, greater shear (posterior and lateral) GRFs were observed during CUT110. While vertical GRFs were 21% greater during CUT110 than CUT45, larger increases in lateral (227%) and posterior (87%) GRFs reflect the higher redirection demands during the 110° cut. GRFs were the largest predictors of knee valgus moments during both tasks; greater forces were related to greater moments. During CUT45, vertical GRF was the largest predictor explaining 37% of the variance. Lateral GRF explained an additional 19% of the variance in knee valgus moment. These findings are consistent with previous data assessing predictors of frontal plane knee loading during cutting.[15] During CUT110, posterior GRF was the only GRF variable to predict knee valgus moment, explaining 21% of the variance. Contrary to our hypothesis, lateral GRF was not associated with knee valgus moment during CUT110, despite the greater redirection requirements. However, previous studies suggest that interpretation of raw GRF data with respect to segment mechanics is difficult when the task requires movement outside the original plane of movement.[25] As such, it is difficult to interpret the effect of the posterior GRF on knee frontal plane moments during CUT110. However, the inclusion of lateral and posterior GRFs in the prediction models for CUT 45 and CUT110, indicate that larger shear forces during cutting contribute to as much as 20% of the variance in knee frontal plane loading during both tasks.

Task differences in hip frontal and transverse plane kinematics suggest that redirection of the body was accomplished through different mechanisms. Athletes demonstrated smaller hip internal rotation angle and greater hip abduction angle at initial contact during CUT110. Previous studies suggest that individuals pre-rotate toward the new direction during cutting.[7,15] Given the larger redirection requirements of CUT110, we hypothesized that greater hip internal rotation would be observed during CUT 110. An *a posteriori* analysis of body rotation (pelvic position with respect to the original direction of progression) revealed that during CUT110, subjects’ did indeed pre-rotate, but not through hip rotation. Greater pelvic rotation was noted during CUT110 than CUT45 (37.15 ± 3.32° versus 6.95 ± 1.20°). In the frontal plane, over 4 times greater hip abduction was observed at initial contact during CUT110, suggesting that greater hip abduction is necessary to redirect the body at the greater angle.

Despite the differences between the tasks in hip mechanics, hip rotation was found to be a common predictor of knee valgus moment during both tasks. Together with knee valgus angle, greater hip internal rotation predicted larger knee valgus moments during both CUT110 and CUT45. Hip internal rotation angle at initial contact has been previously identified as a predictor of knee valgus loading during 45° cutting tasks[7,15] and was found to also be a predictor during cuts performed to larger angles in the current study. Further work is needed to understand this relationship and determine how altering hip rotation during cutting effects knee loading.

As expected, sex-related differences were observed in peak knee valgus moment; however, of the variables that predicted knee valgus moments, differences between men and women were only found in knee valgus angle, vertical and posterior GRFs. This suggests that hip internal rotation angle and lateral GRFs did not contribute to the sex differences knee valgus moment. However, trends in GRF data suggest that differences in vertical and posterior GRFs may have contributed to the sex differences observed in knee valgus moments. While females had greater knee valgus moments overall, it appears that larger differences between males and females were present during CUT110 (Figure 2). A similar pattern was noted in the vertical and posterior GRF data (Figure 3) suggesting that sex differences in loading during cutting may become more pronounced when performing tasks that require greater redirection.

This study is the first to assess cutting tasks performed at angles larger than 90°. While the kinematic and GRF data suggest that the demands of the tasks differ, these data are limited to variables that have been previously related to knee valgus moments. A more comprehensive comparison of kinematics and kinetics is needed to understand the demands of cutting tasks executed to different angles. These data suggest that similar variables are associated with knee valgus loading during both tasks. Given the potential differences in task demands it is not clear how changing these variables would alter task performance or knee frontal plane loading.

CONCLUSION

Together these data demonstrate that cutting tasks with larger redirection demands (e.g., CUT110) result in greater frontal plane knee loading. Similar kinematics, greater hip internal rotation angle and knee valgus angle, predict larger knee valgus moments during cuts performed to smaller (45°) and larger (110°) angles. While vertical GRFs were the largest predictor of knee valgus moments during 45° cutting, shear forces explained as much as 20% of the variance during cutting to both 45° and 110°. Disproportionally greater loading exhibited by females during CUT110 suggests that cutting to larger angles may present a greater challenge to females. Reducing shear GRFs during cutting to larger angles may work to reduce knee valgus moments and thereby reduce risk for injury. However, further work is needed before these data can be applied to specific training recommendations for the reduction of knee valgus loading during cutting.

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Clinical relevance

Reducing vertical and shear GRFs during cutting maneuvers may reduce knee valgus moments and thereby potentially reduce risk for ACL injury.

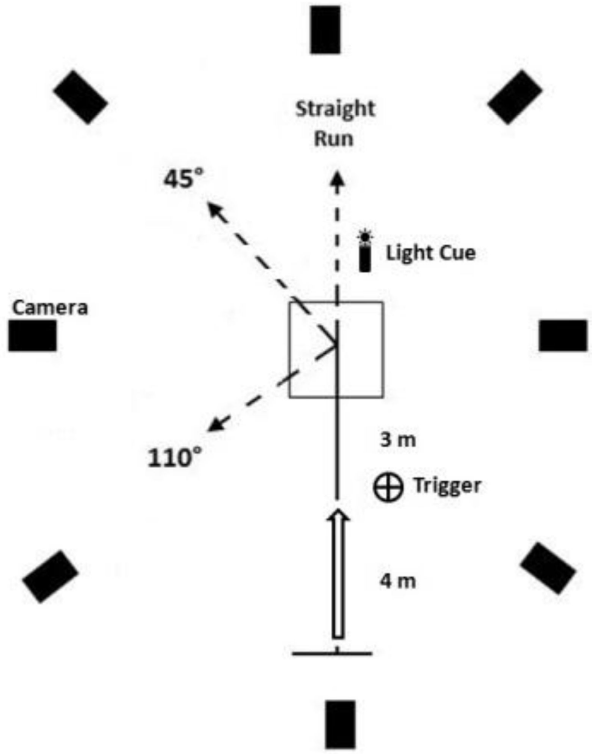

FIGURE 1.
Experimental set-up for the side-step cutting tasks. Open arrow indicates original plane of progression. Dashed lines indicate the direction of the three possible tasks: straight run, cutting to 45°, or cutting to 110°. Light cue was triggered 3 meters prior to force plate contact and randomly indicated cutting direction.

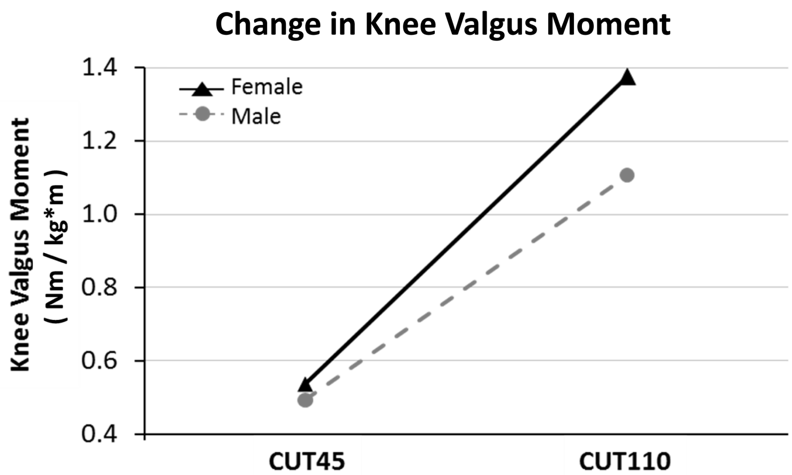

FIGURE 2.

Greater knee valgus moment in females and during CUT110. A trend toward a greater difference between males and females during CUT110 compared to CUT45.

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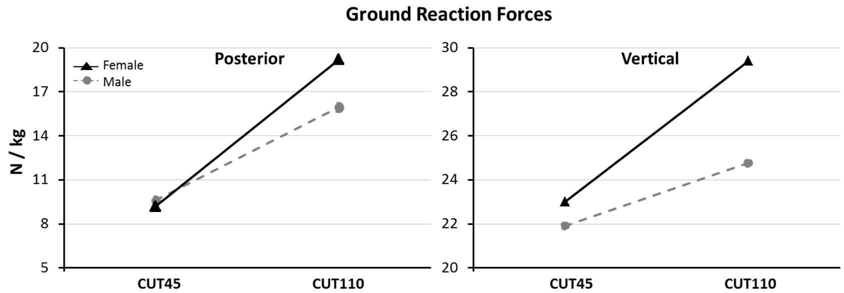

FIGURE 3.
Greater posterior GRF in females and during CUT110. Greater difference between males and females during CUT110 compared to CUT45. Greater vertical GRFs in females and during CUT110. A trend toward a greater difference between males and females during CUT110 compared to CUT45.

TABLE 1

Characteristics of the Participants. Mean ± Standard Deviation (Range)

	Male (n=25)	Female (n=20)	Total (n=45)
Age (years)	18.76±2.09 (16–23)	18.25±2.15 (16–23)	18.53±2.11 (16–23)
Height (meters)	1.80±0.07 (1.66–1.96)	1.63±0.07 (1.50–1.77)	1.72±0.11 (1.50–1.96)
Mass (kilograms)	75.58±8.02 (57.70–89.10)	59.55±7.38 (45.70–76.10)	68.46±11.11 (45.70–89.10)

TABLE 2

Variables analyzed during the side-step cutting tasks. Results are mean ± standard error (*unstandardized residuals*).

	CUT45		CUT110		
	Male	**Female**	**Male**	**Female**	**Significance**
Knee valgus angles	0.61 ± 0.56	3.61 ± 0.63	1.33 ± 0.60	3.65 ± 0.56	Angle: P = 0.26 **Sex: P = 0.001** Angle × Sex: P = 0.31
Hip abduction	7.43 ± 1.08	2.48 ± 1.38	20.75 ± 1.29	17.33 ± 1.49	**Angle: P < 0.001** **Sex: P = 0.01** Angle × Sex: P = 0.41
Hip internal rotation	8.32 ± 1.43	7.20 ± 1.28	6.90 ± 1.41	3.87 ± 1.65	**Angle: P = 0.03** Sex: P = 0.25 Angle × Sex: P = 0.36
Knee valgus moment	0.49 ± 0.06 *(−0.41)*	0.54 ± 0.07 *(−0.31)*	1.11 ± 0.09 *(0.22)*	1.38 ± 0.11 *(0.55)*	**Angle: P < 0.001** **Sex: P = 0.02** Angle × Sex: P = 0.07
Vertical GRF	21.91 ± 1.30 *(−2.75)*	22.99 ± 1.30 *(−1.57)*	24.76 ± 0.76 *(0.11)*	29.40 ± 1.24 *(4.87)*	**Angle: P < 0.001** **Sex: P = 0.04** Angle × Sex: P = 0.07
Posterior GRF	9.59 ± 0.66 *(3.94)*	9.20 ± 0.66 *(4.13)*	15.96 ± 0.53 *(−2.46)*	19.22 ± 0.92 *(−5.98)*	**Angle: P < 0.001** **Sex: P = 0.04** **Angle × Sex: P = 0.001**
Lateral GRF	0.34 ± 0.09 *(0.56)*	0.53 ± 0.15 *(0.40)*	1.31 ± 0.21 *(−0.40)*	1.55 ± 0.24 *(0.49)*	**Angle: P < 0.001** Sex: P = 0.39 Angle × Sex: P = 0.88

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TABLE 3

Stepwise linear regression for the dependent variable knee valgus moment

Model CUT45	Variable	R	R^2	R^2 Change	Significance
1	Vertical GRF	0.607	0.369	0.369	< 0.001
2	Vertical GRF Lateral GRF	0.745	0.555	0.186	< 0.001
3	Vertical GRF Lateral GRF Hip Internal Rotation Angle	0.785	0.616	0.061	0.015
4	Vertical GRF Lateral GRF Hip Internal Rotation Angle Knee Valgus Angle	0.814	0.663	0.047	0.023
Model CUT110	**Variable**	**R**	R^2	R^2 **Change**	**Significance**
1	Posterior GRF	0.460	0.193	0.211	0.001
2	Posterior GRF Hip Internal Rotation Angle	0.625	0.361	0.179	0.001
3	Posterior GRF Hip Internal Rotation Angle Knee Valgus Angle		0.415	0.065	0.033