THE INFLUENCE OF ANKLE DORSIFLEXION RANGE OF MOTION ON UNANTICIPATED CUTTING KINEMATICS

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Abstract

Purpose: Explore whether dorsiflexion range of motion (ROM) influences cutting kinematics.

Methods: Dorsiflexion ROM was measured in 42 individuals using the Weight-Bearing Lunge Test (WBLT). Unanticipated cutting kinematics were collected at initial contact (IC) and between IC and maximum knee flexion using three-dimensional motion and inertial measurement unit methods. Multiple linear regressions with sex as a confounder were used to explore the relationship between kinematic variables and WBLT dorsiflexion ROM for both legs.

Results: WBLT dorsiflexion ROM values were 51.33 ± 6.48° and 50.21 ± 7.00° on dominant and non-dominant legs, respectively. For dominant leg cutting, transverse plane knee ROM increased 0.20° ($p = 0.037$), sagittal plane trunk ROM increased 0.16° ($p = 0.044$), and trunk flexion at IC decreased 0.39° ($p = 0.009$) for each degree of WBLT dorsiflexion ROM measured. Males had 5.89° greater trunk flexion at IC than females. For non-dominant leg cutting, peak lateral trunk flexion towards the stance leg, and sagittal and coronal plane hip ROM increased 0.36° ($p = 0.039$), 0.24° ($p = 0.017$), and 0.21° ($p = 0.005$) for each degree of dorsiflexion ROM, respectively.

Conclusions: Dorsiflexion ROM influence cutting kinematics and may contribute to ACL injury.

Keywords: Weight bearing lunge test, Anterior Cruciate Ligament, injury risk, sport-related injury

Highlights

- Dorsiflexion ROM influence kinematics of a sport-specific side-step cutting task

- Dorsiflexion ROM may contribute to ACL injury mechanisms during cutting maneuvers
- Clinical measures of dorsiflexion ROM may be useful for screening in cutting sports

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Contributions:

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Ivana Hanzlíková, Jim Richards and Kim Hébert-Losier. The first draft of the manuscript was written by Ivana Hanzlíková and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Introduction

Landing technique is an important lower extremity injury risk factor. Devita and Skelly[1] compared stiff versus soft landing techniques and showed greater kinetic energy absorption by the muscular system (~19%) and lower vertical ground reaction force (~30%) during soft compared to stiff landings. These findings indicate that the muscles crossing the lower extremity joints absorb more energy during soft landings and decrease the impact stresses on the musculoskeletal system, presumably reducing the probability of injury.

Ankle dorsiflexion range of motion (ROM) plays a prominent role in landing biomechanics and technique[2-4]. Previous studies have concluded that limited passive dorsiflexion ROM is related to lower ankle, knee, and hip sagittal plane displacement and greater ground reaction forces during single-leg and double-leg landings in healthy individuals as well as persons with chronic ankle instability[2-4]. The magnitude of the ground reaction forces during landing has been strongly associated with impact stresses on the body structures and is a risk factor for lower extremity injuries, in particular to the Anterior Cruciate Ligament (ACL)[5, 6]. Furthermore, several studies have concluded that individuals with a history of an ankle injury have limited dorsiflexion ROM, which results in a more erect landing posture, greater ground reaction force, and potentially higher re-injury rate[2, 4].

In sport, the ankle and knee are the most commonly injured sites and often involve unilateral loading during changes of direction, sudden decelerations, and landings[7]. Not surprisingly, knee and ankle injuries are most common in American football, soccer, volleyball, basketball, and handball, which are sports with a regular occurrence of ‘risky movements’ (i.e., changes of direction)[7]. Several studies have explored the influence of dorsiflexion ROM on human biomechanics during single-leg or double-leg landings[2-4]; however, the influence of dorsiflexion ROM on cutting maneuvers, which are common in sports with the highest incidence of ankle and knee injuries, is currently unknown.

Therefore, our aim was to explore the influence of ankle dorsiflexion ROM on kinematics during unanticipated side-step cutting maneuvers, and to identify whether limited dorsiflexion ROM is associated with specific movement patterns that may predispose individuals to non-contact ACL and other non-contact lower extremity injuries. We hypothesized that limited dorsiflexion ROM would be associated with a more erect posture at IC and lower ROM of the lower extremity joints.

Materials and methods

Sample size analysis

Since no study so far has explored the correlation between dorsiflexion ROM and cutting biomechanics, we based our sample size requirements on findings from studies examining the association between dorsiflexion ROM and landing kinematic in males and females[2, 3]. Dorsiflexion ROM influences predominantly sagittal plane kinematics[2-4]; and therefore, sample size requirements were calculated based on correlations reported to exist between dorsiflexion ROM and sagittal plane ROM at the ankle ($r = 0.47$), knee ($r = 0.46$ to 0.70), and hip ($r = 0.55$)[2, 3]. From standard two-tailed hypothesis equations using an 80% power ($\beta = 0.05$) and 5% significance level ($\alpha = 0.05$), and to detect the lowest correlation presented ($r = 0.46$), 35 participants were needed. To account for a potential 20% withdrawal or missing data, we recruited 42 participants.

Participants

The inclusion criteria were regular participation in a team sport that involved cutting and being free from any injury or illness that had prohibited or limited physical activity in the 6 months prior to testing. Only individuals participating in a team sport were included given a greater number of unanticipated cutting movements present due to players interactions. A Health Research Ethics Committee approved the study protocol [HREC(Health)2018#27], which adhered to the Declaration of Helsinki. All participants signed a written informed consent document prior to participating that explained the potential risks associated with testing.

Experimental procedure

Participants were familiarized with the experimental protocol and all testing was completed in one session. After completing the self-administered short-form International Physical Activity Questionnaire[8], an experienced physiotherapist measured ankle dorsiflexion ROM using the Weight-Bearing Lunge Test (WBLT). The WBLT is considered to be representative of ankle function during sporting activities due to its weight-bearing nature[9]. The WBLT has been shown to be reliable, with an intrarater reliability intraclass correlation coefficient (ICC) of 0.85 to 0.99 and interrater reliability ICC of 0.80 to 0.99[9]. The WBLT has also been validated against 2D motion capture analysis for the assessment of dorsiflexion ROM (r = 0.71 to 0.76)[10]. There are several WBLT measurement techniques. Placing a digital inclinometer 15 cm below the tibial tuberosity demonstrates the best validity against 2D motion capture (r = 0.76)[10], and was therefore used in our study (Figure 1). One trial of the WBLT was measured for each lower extremity using a digital inclinometer (Bevel Box, Angle Sensor Technology).

After the WBLT was completed, the kinematics during an unanticipated side-step cutting maneuver were recorded. For the side-step cutting maneuver, participants started five meters in front of the target cutting area. When participants moved within the target area, timing gates (Swift Performance SpeedLight™) triggered one of two lights in a randomized order to signal the cutting direction (Figure 2). Participants were asked to perform a side-step cutting maneuver similar to that during active game play. During cutting, participants were required to stay between two lines that were taped on the floor, which indicated a cutting angle between

60° and 90° (Figure 2). A minimum approach speed of 3.5 m/s at the penultimate foot contact was required based on previous studies to mimic a typical game setting[11]. Trials performed at a slower speed or outside of the taped lines were disregarded and repeated. After a familiarization period of typically two attempts, each participant completed three successful repetitions of side-step cutting maneuvers on the dominant and non-dominant legs. For right-leg dominant participants, cutting towards the left side represented dominant leg cutting (i.e., right leg cutting). The Perceived Recovery Status Scale was used to monitor subjective ratings of recovery[12]. To ensure sufficient recovery times between trials, participants needed to self-report ratings ≥ 7 before starting the next trial; else, rest periods were extended. Participants wore their own sport shoes for testing.

Figure 1. Weight-Bearing Lunge Test. A digital inclinometer placed 15 cm below the tibial tuberosity.

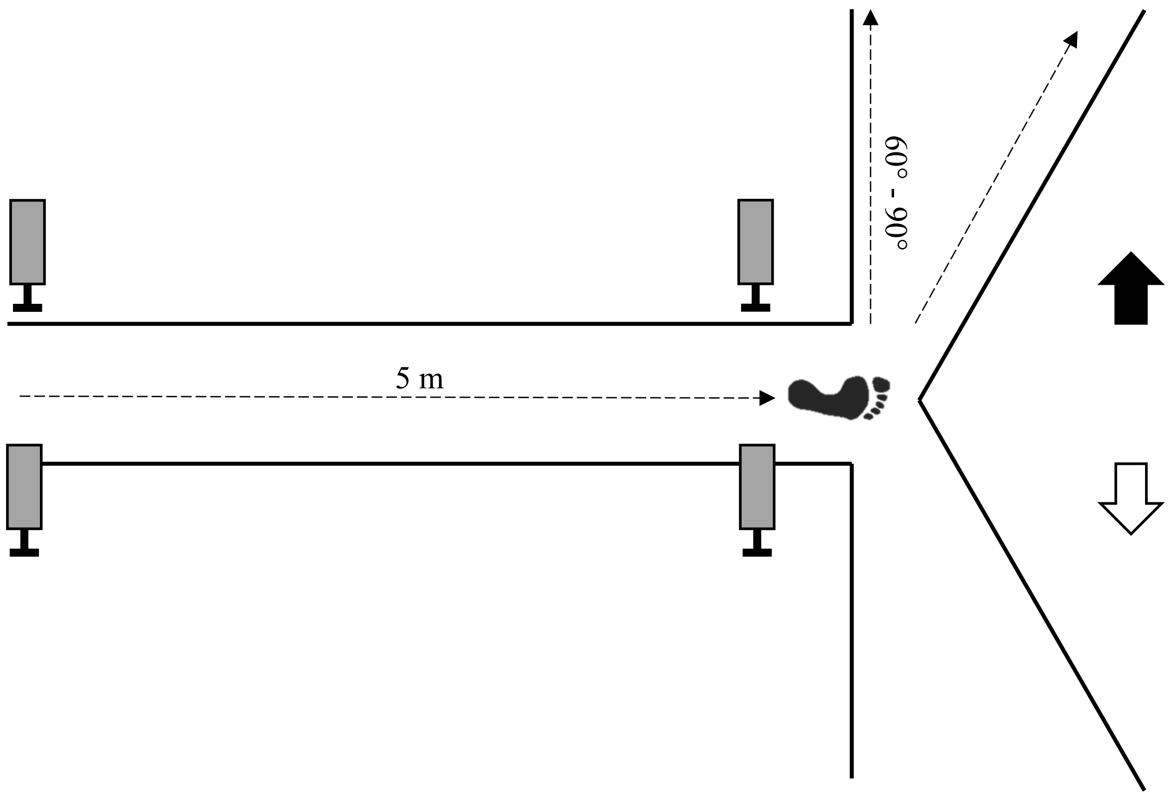

Figure 2. A schematic representation of the unanticipated side-step cutting maneuver. The task involves participants approaching 5 m towards a cutting area. At the cutting area, participants perform a 60° to 90° cut to the left or right based on the light signal triggered by timing gates.

Instrumentation

Whole-body motion was recorded during all cutting tasks using an 8-camera Oqus 700+ 3D motion capture system at 200 Hz using the Qualisys Track Manager software version 2019.1 (Qualisys AB, Gothenburg, Sweden). Forty-two 12.5-mm retroreflective markers and five clusters were taped onto the skin and shoes, which were modelled using the Calibrated Anatomical System Technique[13] with an additional cluster placed on the right side of the pelvis to improve segment tracking (Figure 3). Due to absence of force plates, one inertial measurement unit (IMU) sensor (Delsys Trigno IM sensors, Delsys Inc., MA, USA) collecting at 148 Hz was attached to the sacrum and synchronized with the 3D motion capture system to measure pelvis linear accelerations, which has been previously associated with ground reaction forces[14].

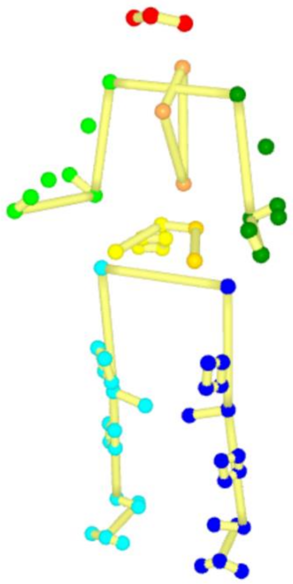

Figure 3. Marker placement.

Data processing

The raw data were exported to the .c3d format and processed using Visual3D Professional™ software version 6.01.36 (C-Motion Inc., Germantown, Maryland, USA). From the reference set of markers, a full-body biomechanical model with six degrees of freedom at each joint and 13 rigid segments was constructed, with the local coordinates of all body segments derived from a static trial captured prior to the cutting maneuver. To remove the initial offset between foot and ankle and to create more clinically relevant ankle joint angles, virtual foot segments were constructed by projecting lateral and medial malleoli and foot center markers onto the floor to align the foot and laboratory coordinate systems. Any gaps in the marker data up to 10 frames were interpolated using a third order polynomial fit algorithm. Subsequently, marker data were filtered using a fourth order low-pass Butterworth filter with a cut off frequency of

15 Hz. The analog signal from the pelvis IMU sensor was filtered using a fourth order low-pass Butterworth filter with a cut off frequency of 80 Hz. IMU data were visually assessed using a range of cut-off frequencies (15 to 100 Hz), and 80 Hz was confirmed as the best at preserving all high-frequency signal characteristics, while also removing noise. The sacrum IMU acceleration data were corrected based on the pelvis angle in all three planes to estimate vertical accelerations.

Kinematic parameters were calculated using an XYZ cardan sequence equivalent to the joint coordinate system proposed by Grood and Suntay[15]. Based on the previous studies exploring dorsiflexion ROM and landing biomechanics[2-4], we expected kinematic changes predominantly in the sagittal plane. We were notably interested in examining values at IC and throughout the loading phase of the cutting maneuver, as examined elsewhere[2, 3]. The kinematic values at IC, and the minimum, maximum, and range values between IC and maximal knee flexion for ankle, knee, hip, and trunk angles and pelvis linear accelerations in all three planes were extracted for dominant and non-dominant leg cutting maneuvers. Furthermore, foot-ground angles in all three planes one frame before IC were extracted to explore pre-landing strategies[16]. Note that trunk angles were calculated relative to the laboratory coordinate system. IC was defined as the instance when the cutting-leg foot center of gravity vertical acceleration (z) reached a maximum value. Furthermore, the pelvis center of gravity velocity at IC and cutting angle during the cutting maneuver were extracted to quantify cutting performance.

Statistical analysis

Kinematic data from the three trials on each leg were averaged and used for further processing. Mean ± standard deviation and range (minimum to maximum) values were calculated for all variables as descriptive statistics. Given that our data showed significant differences related to lower extremity dominance during sport-specific cutting maneuvers, we analyzed dominant and non-dominant legs separately. Multiple linear regressions were used to model the relationship between kinematic variables during cutting maneuvers, dorsiflexion ROM, and sex. We controlled for sex due to the significant differences reported to exist in kinematic measures between sexes during cutting maneuvers[17]. When the sex confounder was not significant ($p > 0.05$), it was removed from the model. Note that no analysis was performed if only the sex confounder was significant as sex differences were not the aim of this study. We set the significance level at $\alpha \leq 0.05$ for all analyses. Statistical analyses were performed using Microsoft® Excel for Office 365 MSO and RStudio® Version 1.1.463 with R version 3.5.2.

Results

Forty-two individuals (25 males and 17 females) volunteered to participate. Age, height, and mass (mean ± standard deviation) for males were 23.6 ± 4.1 years (range 17 to 32 years), 182.2 ± 6.4 cm, and 85.0 ± 11.9 kg; and for females were 22.2 ± 5.7 years (range 16 to 35 years), 169.1 ± 6.0 cm, and 63.7 ± 6.8 kg. The majority of participants (93%) were right-leg dominant, assessed by the preferred leg when kicking a ball. According to the International Physical Activity Questionnaire, level of activity was high, moderate, and low in 60%, 38%, and 2% of participants, respectively. From our sample, 31% of participants played soccer, 26% rugby, 17% frisbee, 14% netball, 7% basketball, and 5% field hockey. Participants were involved in physical activity 3 times per week (median), on average for 7 hours per week. Overall, the mean cutting angle was 58.3 ± 9.8° and cutting speed at IC was 3.4 ± 0.5 m/s. Mean dorsiflexion ROM from the WBLT was 51.3° ± 6.5° (range: 35.9° to 70.0°) on the dominant leg and 50.2 ± 7.0° (range: 33.5° to 71.5°) on the non-dominant leg. Mean values and standard deviations for the kinematic variables measured during the dominant and non-dominant leg cutting maneuvers are presented in Table 1. Data from all 42 participants were analyzed, and there were no missing data.

For dominant leg cutting, significant regression equations were found for transverse plane knee ROM ($F_{(1, 39)} = 4.65$, $p = 0.037$, $R^2 = 0.11$), sagittal plane trunk ROM ($F_{(1, 39)} = 4.35$, $p = 0.044$, $R^2 = 0.10$), and trunk flexion angle at IC ($F_{(2, 39)} = 5.40$, $p = 0.009$, $R^2 = 0.22$), Figure 4. Transverse plane knee ROM increased by 0.20° and sagittal plane trunk ROM increased by 0.16° for each degree of dorsiflexion ROM measured during the WBLT. Trunk flexion angle at IC decreased by 0.39° for each degree of dorsiflexion ROM measured during the WBLT, with males exhibiting 5.89° greater trunk flexion at IC than females.

For non-dominant leg cutting maneuvers, significant regression equations were found for peak lateral trunk flexion towards the stance leg ($F_{(1, 39)} = 4.56$, $p = 0.039$, $R^2 = 0.10$), sagittal plane hip ROM ($F_{(1, 39)} = 6.17$, $p = 0.017$, $R^2 = 0.14$), and coronal plane hip ROM ($F_{(1, 39)} = 8.79$, $p = 0.005$, $R^2 = 0.18$), Figure 5. Peak lateral trunk flexion towards the stance leg, sagittal plane hip ROM, and coronal plane hip ROM increased 0.36°, 0.24°, and 0.21° for each degree of dorsiflexion ROM measured during the WBLT, respectively.

Table 1. Means and standard deviation (SD) of kinematics variables measured during unanticipated side-step cutting from initial contact (IC) to maximal knee flexion.

		DOMINANT LEG CUTTING		**NON-DOMINANT LEG CUTTING**	
	Variable	**Mean**	**SD**	**Mean**	**SD**
Foot-ground angles (°)[a]	Heel strike angle	3.97	6.54	4.90	6.30
	Eversion (-)	-11.32	9.36	-12.16	8.36
	Internal rotation	4.15	11.46	3.72	11.63
Ankle angles (°)	Peak plantar flexion (-)	-10.93	10.85	-12.89	6.10
	Peak dorsiflexion	20.34	10.32	17.08	8.48
	Plantar flexion at IC (-)	-10.47	10.92	-11.91	6.16
	Sagittal plane ROM	31.27	8.97	29.96	6.95
	Min adduction	17.87	6.86	15.88	5.66
	Max adduction	32.38	6.52	32.83	7.13
	Adduction at IC	18.26	6.70	16.04	5.70
	Coronal plane ROM	14.51	6.58	16.95	7.09
	Min external rotation (-)	-2.00	11.93	-0.82	8.53

	Max external rotation (-)	-12.69	11.71	-10.61	8.56
	External rotation at IC (-)	-5.07	11.50	-3.40	8.47
	Transverse plane ROM	10.69	3.61	11.43	4.02
Knee angles (°)	Min flexion	26.84	5.78	25.53	4.87
	Max flexion	56.67	7.39	56.69	7.60
	Flexion at IC	27.16	5.83	25.70	4.94
	Sagittal plane ROM	29.82	5.93	31.16	7.01
	Min valgus (-)	2.70	5.25	3.74	5.55
	Max valgus (-)	12.65	7.37	15.42	7.69
	Valgus at IC (-)	5.27	5.25	6.08	5.13
	Coronal plane ROM	9.95	3.91	11.69	4.11
	Peak external rotation (-)	-3.67	6.64	-3.17	8.23
	Peak internal rotation	8.67	6.78	9.85	8.68
	Internal rotation at IC	0.93	8.27	1.47	8.97
	Transverse plane ROM	12.34	3.98	13.02	4.21
Hip angles (°)	Min flexion	26.08	12.38	23.35	15.27
	Max flexion	36.80	10.96	36.97	14.32
	Flexion at IC	35.13	10.47	35.66	13.86
	Sagittal plane ROM	10.72	4.36	13.62	4.60
	Min abduction (-)	-10.84	6.57	-12.17	7.55
	Max abduction (-)	-17.89	6.81	-19.65	7.01
	Abduction at IC (-)	-12.81	7.00	-17.08	7.12
	Coronal plane ROM	6.96	2.36	7.48	3.38
	Peak external rotation (-)	-10.08	9.24	-19.61	12.64
	Peak internal rotation	7.62	9.09	1.24	10.70
	Internal/external (-) rotation at IC	3.96	9.92	-2.45	10.14
	Transverse plane ROM	17.70	6.65	20.85	7.48
Trunk angles (°)[b]	Min flexion	8.30	8.37	7.87	9.01
	Max flexion	15.03	8.15	16.17	9.60
	Flexion at IC	9.02	8.64	8.31	9.40
	Sagittal plane ROM	6.73	3.31	8.30	4.78
	Peak lateral flexion away from stance leg (-)	-3.76	7.59	-2.57	6.87
	Peak lateral flexion towards stance leg	0.75	6.56	2.22	7.68
	Lateral flexion away from stance leg at IC (-)	-0.31	5.73	-1.32	6.20
	ROM in coronal plane	4.51	2.08	4.78	2.59
	Min rotation away from the stance leg	2.34	12.43	2.12	15.24
	Max rotation away from the stance leg	15.23	12.65	14.48	15.75
	Rotation away from the stance leg at IC	3.37	10.95	3.54	12.90
	ROM in transverse plane	12.89	4.81	12.36	5.29
Pelvis linear acceleration (m/s^2)	Minimal vertical acceleration	-8.69	2.79	-7.36	2.58
	Maximal vertical acceleration	1.14	1.06	1.08	0.87
	Vertical acceleration at IC	0.44	0.74	0.37	0.52
	Range in sagittal plane	9.82	3.40	8.45	3.11
	Minimal medio-lateral acceleration	-2.61	2.20	-7.13	3.24
	Maximal medio-lateral acceleration	7.93	3.53	2.78	2.18
	Medio-lateral acceleration at IC	-0.58	0.78	0.69	1.03
	Range in coronal plane	10.54	4.45	9.92	3.59
	Minimal anterior-posterior acceleration	-1.53	1.57	-1.12	1.01
	Maximal anterior-posterior acceleration	4.81	1.75	4.63	1.41
	Anterior-posterior acceleration at IC	0.16	1.12	0.41	1.08
	Range in transverse plane	6.34	2.88	5.75	2.20

Abbreviations: IC, initial contact; Max, maximal; Min, minimal; ROM, range of motion from initial contact to maximal knee flexion.

[a]Foot-ground angles extracted one frame before initial contact

[b]Trunk angle relative to the lab coordination system

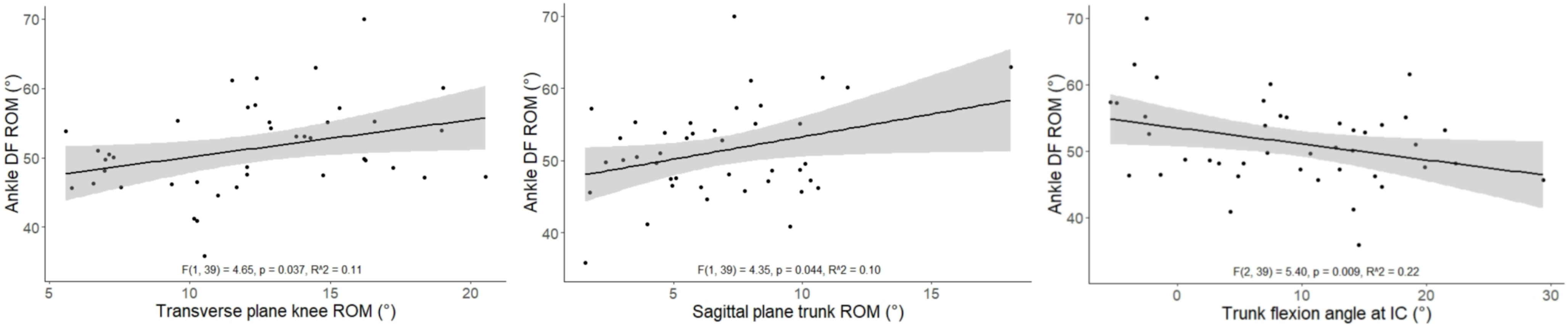

Figure 4. Significant associations between dorsiflexion (DF) range of motion (ROM) measured during the Weight Bearing Lunge Test and dominant leg side-step cutting kinematics.

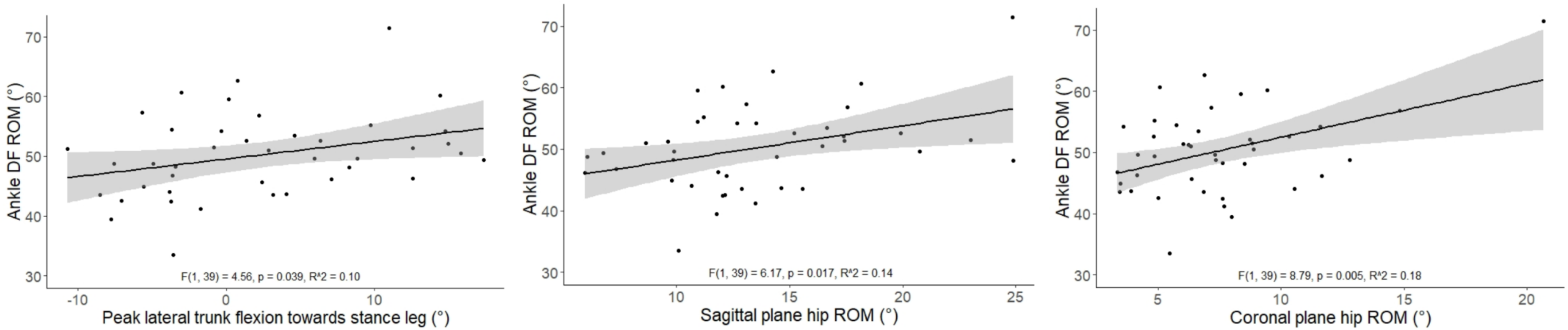

Figure 5. Significant associations between dorsiflexion (DF) range of motion (ROM) measured during the Weight Bearing Lunge Test and non-dominant leg cutting kinematics.

Discussion

As hypothesized, the ankle dorsiflexion ROM tested using the WBLT significantly influenced sagittal plane kinematics during unanticipated side-step cutting maneuvers. Significant associations between coronal and transverse plane kinematics and dorsiflexion ROM from the WBLT were also found. Given that some of these kinematic variables from the cutting task have been linked to non-contact ACL injuries[18-20]; dorsiflexion ROM, as measured using the WBLT, may contribute to the ACL injury mechanisms.

Significant associations in the sagittal plane

During dominant leg cutting, decreased trunk flexion at IC was significantly associated with increased dorsiflexion ROM tested by the WBLT. Decreased trunk flexion at IC may play role in ACL injury mechanism as indicate findings from video analyses of ACL injury situations whereby injured athletes demonstrated less peak trunk flexion at IC (mean: 1.6° to 4.0°) during injury compared to uninjured controls (mean: 14.0° to 16.0°)[18, 19]. Furthermore, Hashemi et al.[21] stated that the upright and extended position of the trunk causes the center of mass to be positioned posteriorly relative to the knee joint; encouraging the knee to flex more than the hip, which results in anterior translation of the tibia and ACL strain.

The findings from the current study showed that participants with greater dorsiflexion ROM presented with a more extended or upright trunk position at IC, which could increase their risk of ACL injury. Noteworthy, however, is that these participants also demonstrated greater sagittal plane trunk ROM during the loading phase of the dominant leg during cutting. It may be that participants with greater dorsiflexion ROM compensate for the decreased trunk flexion at IC by having a greater trunk ROM during the loading phase. Although trunk flexion contributes to absorbing impact forces during weight acceptance to a lesser extent than the ankle, knee, and hip; trunk flexion ROM allows the generation of hip moments to help reduce stress on the knee joint during weight acceptance[22].

During non-dominant leg cutting in this study, the sagittal plane hip ROM was lower in individuals with less dorsiflexion ROM recorded using the WBLT. The contribution of sagittal plane hip ROM to ACL injury is supported by video analyses showing that athletes during an ACL injury situation have greater peak hip flexion at IC and 160 milliseconds after IC, but limited hip ROM in the sagittal plane compared to uninjured controls (5.1° vs 15.4°)[20]. One possible explanation is that decreased sagittal plane ROM of the lower extremity joints shortens the loading phase, therefore limiting the time over which landing forces are dissipated[6]. Loading rate and magnitude of ground reaction forces are both risk factors for lower extremity injuries and have been linked with ACL injury[5, 6]. However, despite shown to be significantly correlated to ground reaction forces[14], pelvis linear accelerations in this study were not significantly associated with ankle dorsiflexion ROM. Direct measurements of ground reaction forces would be needed to confirm similarities in forces during unanticipated cutting and their association with dorsiflexion ROM. Besides sagittal plane hip ROM, sagittal plane knee and ankle ROM also largely contribute to ground reaction forces[1, 5]. It is possible that limited sagittal plane ROM in one joint is partly compensated with greater ROM in other lower-extremity joints to mitigate impact forces.

Our study did not show any significant association between dorsiflexion ROM assessed using the WBLT and ankle or foot-ground angles during cutting maneuvers. These results contradict previous findings that identified significant correlations between static dorsiflexion ROM and ankle kinematics during a single-leg drop-landing task[2]. Furthermore, static dorsiflexion ROM measures have been shown to influence sagittal plane landing biomechanics during various jump or drop-landing tasks, explaining between 17% to 55% of the variance in sagittal plane ankle, knee, and hip motion[2, 3]. On the other hand, the ankle dorsiflexion ROM explained only 10% to 22% of the variance across the sagittal plane cutting kinematic variables found to be significantly associated with dorsiflexion ROM in our study. Landing and side-step cutting maneuvers have distinct kinematic and kinetic characteristics; with cutting maneuvers being more mechanically demanding for the knee and hip, and landing tasks more demanding for the ankle[23]. During single-leg landing, peak ankle joint moments, power, and work were greater and the plantarflexion angle at IC was almost tripled when compared to cutting maneuvers[23]. The greater mechanical demands on the ankle during landing compared to cutting may explain the greater influence of ankle dorsiflexion ROM on sagittal plane landing kinematics and kinetics, specifically at the ankle, compared to cutting[2-4].

Significant associations in the coronal and transverse plane

In this study, the ankle dorsiflexion ROM had a greater influence on coronal and transverse plane kinematics compared to previous studies exploring various jump-landing tasks[2-4]. Compared to jump-landing, cutting maneuvers are more demanding in terms of controlling coronal and transverse plane movements[24]. For instance, knee valgus moments have been reported to be six times greater in cutting compared to a drop-jump task[24]. For this reason, excessive or limited ankle ROM may result in greater alteration of more proximal segments in the coronal or transverse planes during cutting maneuvers than the previously explored jump-landing tasks.

It has been shown that excessive knee internal and external rotation may contribute to ACL injury mechanisms[25]. However, in our study, peak knee internal and external rotations were not significantly associated with ankle dorsiflexion ROM, although the increased knee ROM in the transverse plane was associated with increased dorsiflexion ROM during dominant leg cutting maneuvers. Similarly, the hip ROM in the coronal plane was associated with increased dorsiflexion ROM during non-dominant leg cutting maneuvers. Greater ranges of motion may be due to increased ligamentous laxity or poor neuromuscular control of the knee and hip joints[26, 27]. Although transverse plane knee ROM and coronal plane hip ROM may not seem impactful in isolation, their effects when compounded with other potential risk factors and impact on other segment positions may contribute to non-contact ACL injury.

In our study, greater peak lateral trunk flexion towards the stance leg during non-dominant leg cutting was associated with increased ankle dorsiflexion ROM measured using the WBLT. Coronal plane trunk position plays an important role in non-contact lower-extremity injuries[28]. During all movements, the vertical ground reaction force is directed towards the center of mass, which is located in the trunk segment. The trunk contains approximately half of the body mass; and therefore, if the trunk moves laterally the position of the center of mass moves laterally as well. A more laterally-oriented vertical ground reaction force produces a greater lateral lever arm relative to the knee joint center and increases the knee valgus moment[28]. Moreover, video analysis of ACL injuries has confirmed that lateral trunk movement is coupled with knee valgus collapse[18]. Both Jamison et al.[29] and Jones et al.[22] concluded that cutting technique with the trunk leaning and rotating towards the stance leg produces greater peak knee valgus and internal rotation moments. Therefore, participants with greater ankle dorsiflexion ROM may be at greater risk of knee injury due to increased peak lateral trunk flexion towards the stance leg.

Practical implications

Our study provides novel evidence regarding how measures from a clinical test of ankle dorsiflexion ROM can relate to kinematic variables during unanticipated cutting maneuvers. Based on our results, it seems that ankle dorsiflexion ROM may influence cutting kinematics and may contribute to the non-contact ACL injury mechanisms. Greater ankle dorsiflexion

ROM was associated with decreased trunk flexion at IC and greater peak lateral trunk flexion towards the stance leg: both of these variables have been associated with increased knee load and ACL injuries[18, 19, 22, 28, 29]. Furthermore, greater dorsiflexion ROM was associated with greater knee ROM in the transverse plane and hip ROM in the coronal plane, which may suggest greater ligamentous laxity of these joints or poorer movement control[26, 27]. On the other hand, lower ankle dorsiflexion ROM was associated with a decreased sagittal plane hip and trunk ROM, which may result in greater stresses on lower-extremity joint structures[20, 22]. Therefore, incorporating whole-body neuromuscular control training using stabilization joint exercises and exercises to improve ankle dorsiflexion ROM may be useful in rehabilitation and injury prevention initiatives for individuals with excessive or reduced ankle mobility, respectively.

Limitations

It is important to note that our study explored the association between ankle dorsiflexion ROM measured using the WBLT and cutting kinematics measured using a 3D system. However, we did not assess if ankle dorsiflexion ROM predicts specific movement patterns or incidence of ACL or other non-contact lower-extremity injuries. Therefore, it is not possible to establish ankle dorsiflexion ROM thresholds that reflect high or low risk of injuries with respect to cutting maneuvers. Prospective studies are needed for these purposes. The main limitation of this study is that joint moments, muscle activation patterns, and ground reaction forces were not included in our biomechanical analysis. However, pelvis linear acceleration, which has been previously associated with ground reaction forces, was measured using an IMU sensor as a proxy measure of ground reaction forces[14]. Furthermore, participants with very mobile and very limited ankle dorsiflexion ROM likely influenced the results from the regression analysis. These extreme ranges were not removed from the analysis given that similar ankle ROM has been reported elsewhere[30]. It may be possible that these participants are the ones with the largest influence of ankle dorsiflexion ROM on their cutting biomechanics and potential risk of injury. Moreover, the dorsiflexion ROM explained only 10% to 22% of variance across the cutting kinematic variables found to be significantly associated with dorsiflexion ROM. Therefore, although ankle dorsiflexion ROM explained some movement patterns that have been linked with ACL injury, other factors potentially play a more important role.

Conclusion

Based on our results, is seems that ankle DF ROM may influence cutting kinematics and contribute to ACL injury risk movement patterns. Therefore, use of a clinical measure of ankle dorsiflexion ROM for screening purposes may be useful in sports where cutting maneuvers are common.

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