Mid-flight Lateral Trunk Bending Increased Ipsilateral Leg Loading during Landing: a Center of Mass Analysis

Running title: Lateral Trunk Bending and Landing

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Acknowledgements

The current study was supported by a student research grant from the College of Health Sciences at the University of Wyoming.

Conflict of interest statement

The authors have no financial or personal conflicts of interest to declare.

Word count (Introduction through Discussion): 3916

Keywords: ACL; Knee; Biomechanics; Kinematics; Kinetics

ABSTRACT

Increased lateral trunk bending to the injured side has been observed when ACL injuries occur. The purpose was to quantify the effect of mid-flight lateral trunk bending on center of mass (COM) positions and subsequent landing mechanics during a jump-landing task. Forty-one recreational athletes performed a jump-landing task with or without mid-flight lateral trunk bending. When the left and right trunk bending conditions were compared with the no trunk bending condition, participants moved the COM of the upper body to the bending direction, while the COM of the pelvis, ipsilateral leg, and contralateral leg moved away from the bending direction relative to the whole body COM. Participants demonstrated increased peak vertical ground reaction forces (VGRF) and knee valgus and internal rotation angles at peak VGRF for the ipsilateral leg, but decreased peak VGRF and knee internal rotation angles at peak VGRF and increased knee varus angles at peak VGRF for the contralateral leg. Mid-flight lateral trunk resulted in an asymmetric landing pattern associated with increased ACL loading for the ipsilateral leg. The findings may help to understand altered trunk motion during ACL injury events and the discrepancy in ACL injuries related to limb dominance in badminton and volleyball.

Introduction

Athletes commonly suffer non-contact anterior cruciate ligament (ACL) injuries during jump-landing tasks (Devetag, Mazzilli, Benis, La Torre, & Bonato, 2016; Hewett, Torg, & Boden, 2009; Kimura et al., 2010; Stuelcken, Mellifont, Gorman, & Sayers, 2016). Small knee flexion angles and increased knee abduction and internal rotation angles along with increased anterior tibial shear forces and tibiofemoral compressive forces are associated with increased ACL loading (Dai, Mao, Garrett, & Yu, 2014). Consistently, ACL injuries typically occur during the early phase of landing when individuals demonstrate small knee flexion angles, increased knee abduction and internal rotation angles, and altered trunk angles (Dai, Mao, Garrett, & Yu, 2015; Hewett et al., 2009; Koga et al., 2010; Krosshaug et al., 2007; Stuelcken et al., 2016). Therefore, jump-landing training with a goal to decrease ACL injury risk has been focused on decreasing impact ground reaction forces, increasing knee flexion, and minimizing non-sagittal plane knee motion (Dai, Garrett et al., 2015; Welling, Benjaminse, Gokeler, & Otten, 2016).

Compared to altered knee kinematics, the relationship between altered trunk motion and increased risk for ACL injury during jump-landing remains unclear. Increased lateral trunk bending to the side of injury has been observed in conjunction with increased knee abduction during ACL injuries in female basketball and netball players (Hewett et al., 2009; Stuelcken et al., 2016). When the foot is fixed on the ground, lateral trunk bending can result in an external hip abduction moment on the bending side, which needs to be balanced by an internal hip adduction moment. Such an internal hip adduction moment may cause the knee to move medially and increase external knee abduction moments during landing (Hewett & Myer, 2011). This mechanical connection between trunk and knee motion provides a plausible explanation for the increased lateral trunk bending observed during ACL injury events. A prospective study supports the connection between trunk control and ACL injury risk by showing that female athletes with increased trunk displacements under sudden perturbation demonstrate increased risk for ACL injury (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007). Previous efforts to understand lateral trunk bending and ACL injury risk, however, have been focused on the landing phase (Hewett & Myer, 2011). Interestingly, badminton and volleyball, two sports that involve mid-flight trunk bending and reaching of the dominant arm, have shown increased ACL injury rates to the knee opposite to the dominant arm after landing (Devetag et al., 2016; Kimura et al., 2010). Quantifying how trunk motion prior to landing may affect landing biomechanics can provide additional information for understanding the relationship between lateral trunk bending and ACL injury risk.

Relatively few studies have quantified the effect of mid-flight trunk motion on landing mechanics (Dempsey, Elliott, Munro, Steele, & Lloyd, 2012; Yom, Simpson, Arnett, & Brown, 2014). Dempsey et al. (2012) found that landing after catching a ball that was lateral to the landing leg increased peak knee valgus moments compared with landing after catching a ball medial to the landing leg. The participants in this study, however, were instructed to land with a single leg on a force platform. Single-leg landings result in changes in lower extremity biomechanics that are associated with greater ACL loading compared with double-leg landing (Donohue et al., 2015; Yeow, Lee, & Goh, 2010). Whether participants would unintentionally adopt a single-leg landing after mid-flight trunk motion remains unknown. Yom et al. (2014) demonstrated that landing after mid-flight trunk perturbation induced by an external pulling force resulted in increased peak ground reaction forces, increased knee abduction angles, and decreased knee flexion angles for the leg on the same side of the pulling force. A pulling force simulates ACL injuries that involve mid-flight contact with other players, and whether this contact contributes to the injury situation warrants future investigation. However, this method of trunk perturbation may not represent other ACL injury scenarios, during which individuals have no mid-flight contact with other players.

Athletes commonly perform self-initiated mid-flight lateral trunk bending during sports competition (Kimura et al., 2010). Mid-flight lateral trunk bending may cause re-positioning of segmental centers of mass (COM) and affect landing mechanics. Newton's laws indicate that an individual's whole body COM in the air will demonstrate a parabola shaped trajectory when air resistance is negligible. Therefore, when specific body segments move in one direction relative to the whole body COM in mid-flight, some other segments must move in the opposite direction.

The purpose of the current study was to quantify the effect of mid-flight lateral trunk bending on COM positions and subsequent landing mechanics during a jump-landing task. It was hypothesized that lateral trunk bending in one direction would cause leg movements in the opposite direction. Consequently, the ipsilateral leg would be displaced closer to the whole body COM, while the contralateral leg would be displaced further away from the whole body COM in the mediolateral direction. Based on the literature (Dempsey et al., 2012; Yom et al., 2014), it was also hypothesized that the ipsilateral leg would experience increased peak vertical ground reaction forces (VGRF), decreased knee flexion angles at peak VGRF, and increased knee valgus and internal rotation angles at peak VGRF when landing after mid-flight lateral trunk bending compared with landing without mid-flight lateral trunk bending.

Methods

Participants

Based on previous studies which quantified the effect of mid-flight trunk motion or perturbation on landing biomechanics (Dempsey et al., 2012; Yom et al., 2014), a medium to large effect size was expected for the current study. Assuming a medium effect size of 0.5 for a paired t-test, a sample size of 34 was needed for a type I error at the level of 0.05 to achieve a power of 0.8. Forty-one participants were recruited (sex: 18 males, 23 females; age: 22.0 ± 3.0 years; height: 1.74 ± 0.10 m; mass: 71.0 ± 13.9 kg). All participants preferred to use the right arm to throw a football for further distance. Twenty-eight of them preferred to jump off the right leg for a further distance. Participants had experience with sports that involved jump-landing tasks and participated in sports or exercise at least two times for a total of two to three hours per week at the time of testing. Exclusion criteria were described in a previous study (Dai, Garrett et al., 2015). This study was approved by the University of Wyoming Institutional Review Board. Participants signed informed consent forms and completed a questionnaire to screen for exclusion criteria prior to data collection.

Procedures

Participants wore a baseball cap, spandex pants, a spandex shirt, and standard athletic shoes (Ghost 5, Brooks Sports Inc. Seattle, WA, USA). Participants completed a standard warm-up including five minutes of running at a self-selected speed on a treadmill and a dynamic stretching protocol. Retroreflective markers were placed on a participant's vertex, gonions, sternum, acromioclavicular joints, olecranon processes, mid-points of radial and ulnar styloid processes, third metacarpal heads, anterior superior iliac spines, posterior superior iliac spines, iliac crests, greater trochanters, lateral thighs, anterior thighs, medial and lateral femoral condyles, superior and inferior shanks, lateral shanks, medial and lateral malleolus, tips of big toes, heels, and the fifth metatarsal heads (Figure 1).

Figure 1 near here

After a static trial, participants performed a vertical counter-movement jump-landing task with or without lateral trunk bending. The jump-landing task was designed to simulate basketball rebounding and volleyball blocking, during which athletes laterally bend their trunk and reach both hands to catch or block a ball. This task also had implication for volleyball spiking and badminton smashing, both of which involved lateral trunk bending and one hand reaching. Participants started with feet shoulder-width apart and one foot on each of the two force platforms. In the Up condition, participants were instructed to jump for maximum height and reach both hands in the up direction without laterally bending their trunk (Figure 2). In the Right Bending or Left Bending condition, participants were instructed to jump for maximum height and bend their trunk to the right or left as far as they could and reach both hands to the right or left when they reach their maximum height (Figure 2). In all three conditions, participants were instructed to land with one foot on each of the two force platforms. A trial was repeated if participants did not land on targeted force platforms. No other instruction regarding body movements or landing techniques was given. Participants practiced each jump-landing task for a minimum of two trials, followed by three official trials. Participants were given a minimum of 30-second rest between trials. The order of the three jump-landing tasks was randomized for each participant.

Figure 2 near here

The three-dimensional positions of retroreflective markers were tracked using eight Vicon Bonita cameras at a sampling frequency of 160 Hz (Vicon Motion Systems Ltd, Oxford, UK). Ground reaction forces were recorded using two Bertec FP4060-10 force platforms at a sampling frequency of 1600 Hz (Bertec Corporation, Columbus, OH, USA). Kinematic and ground reaction force data were collected using Vicon Nexus 1.8.2 software (Vicon Motion Systems Ltd, Oxford, UK).

Data Reduction

Kinematic and ground reaction force data were filtered using fourth-order Butterworth low-pass filters at 15 Hz and 100 Hz, respectively (Dai et al., 2016). Markers placed on the pelvis and lower extremities were calibrated during the static trial and reconstructed during the jump-landing trials using a singular decomposition method (Soderkvist & Wedin, 1993). The hip joint was defined as a fixed point in the pelvis reference frame (Bell, Brand, & Pedersen, 1989). Other joints were defined as described in Table 1. The mass and COM locations of each segment were determined based on the literature (de Leva, 1996). The segmentation method (Hay, 1993) was used to calculate the COM of the whole body and four other major components: the upper body including all segments above the pelvis, the pelvis, and two legs ipsilateral or contralateral to the bending side. Cardan angles with an order of rotation of flexion-extension, right-left lateral bending, and left-right axial rotation were calculated between the global and upper-middle trunk reference frames to quantify trunk angles. Similarly, knee joint angles were calculated as the Cardan angles with an order of rotation of flexion-extension, varus-valgus, and internal-external rotation between the thigh and shank reference frames. Knee joint angles during the static trials were defined as the neutral alignment and subtracted from the angles during jump-landing trials.

Table 1 near here

Takeoff was defined as the first time event when both feet were off the force platforms. Maximum Height was defined as the time event when the whole body COM reached maximum height. First Initial Landing was defined as the time event when the first foot landed on a force platform. Second Initial Landing was defined as the time event when the second foot landed on a force platform. The lateral trunk bending angles and COM of the upper body, pelvis, ipsilateral leg, and contralateral leg positions relative to the whole body COM in the mediolateral direction was calculated at Takeoff, Maximum Height, and First Initial Landing. For the Left Bending and Right Bending conditions, the direction of the bending side was defined as positive. For the Up condition, the right direction was defined as positive and the right leg was the ipsilateral leg. COM positions were normalized as a percentage of the participants' body height.

Time differences between the First and Second Initial Landing were calculated with landing of the ipsilateral leg prior to the contralateral leg defined as positive. ACL injuries typically occur during the first 100 ms after initial contact (Dai et al., 2014). In addition, increased impact GRF, knee valgus and internal rotation angles as well as decreased knee flexion angles are associated with increased ACL loading (Dai et al., 2014). Therefore, the peak VGRF during the first 100 ms after initial landing was quantified for each leg. Knee flexion, valgus, and internal rotation angles at the peak VGRF were extracted for each leg. VGRF was normalized to the participants' body weight. Jump height was calculated relative to the whole body COM during static trials and jump-landing trials to quantify jump performance. Calculations were performed using customized subroutines developed in MATLAB 2016b (MathWorks Inc. Natick, MA).

Statistical Analysis

Data for the three official trials for each jump-landing condition for each participant were averaged for analysis. COM positions, lower extremity kinematic and kinetic variables, and jump height were compared among the three jump-landing conditions using repeated measures analyses of variance (ANOVA). When an ANOVA showed a significant main effect, paired t-tests were performed between each pair of two jump-landing conditions. A type-I error rate was set at 0.05 for the ANOVAs for statistical significance. A procedure was applied to all paired t-tests to control the study-wide false discovery rate at 0.05 (Benjamini & Hochberg, 1995). Cohen's dz was calculated to evaluate the effect size of changes in jump height and landing variables between two jump-landing conditions with Cohen's dz ≥ 0.8 considered "large," $0.5 <$ Cohen's dz < 0.8 considered "medium," and Cohen's dz < 0.5 considered "small" (Cohen, 1988). Statistical analyses were performed using SPSS Statistics 24 software (IBM Corporation, Armonk, NY, USA).

Results

ANOVAs showed significant main effects ($p < 0.05$) for all variables except for knee flexion angles at peak VGRF for both ipsilateral and contralateral legs. A total of 69 paired t-tests were performed for the other 23 variables, and the largest p value for a significant paired t-test was 0.026 after the adjustment for the false discovery rate.

When the Left Bending and Right Bending conditions were compared with the Up condition, participants significantly increased lateral trunk bending (Figure 3) and moved the COM of the upper body (Figure 4) to the bending direction relative to the whole body COM, while the COM of the pelvis (Figure 5), ipsilateral leg (Figure 6), and contralateral leg (Figure 7) moved away from the bending direction relative to the whole body COM from Takeoff to First Initial Landing (Table 2). Some significant differences were also observed between the Left Bending and Right Bending conditions.

Jump height significantly decreased for the Left Bending and Right Bending conditions compared with the Up condition with large effect sizes (Table 3). Participants landed on the ipsilateral leg significantly earlier for the Left Bending condition compared with the Up condition, while a similar trend was observed for the Right Bending condition. The effect sizes for time differences were small. When the Left Bending and Right Bending conditions were compared with the Up condition, participants demonstrated increased peak VGRF and knee valgus and internal rotation angles at peak VGRF for the ipsilateral leg but decreased peak VGRF and knee internal rotation angles at peak VGRF and increased knee varus angles at peak VGRF for the contralateral leg with mostly medium to large effect sizes.

Tables 2-3 near here

Figures 3-7 near here

Discussion

The purpose of the current study was to quantify the effect of mid-flight lateral trunk bending on COM positions and subsequent landing mechanics during a jump-landing task. The findings support the hypothesis that mid-flight lateral trunk bending in one direction would cause leg movements in the opposite direction. Since participants jumped vertically, the mid-flight trajectory of the whole body COM should be close to a straight line. Lateral trunk bending was characterized by lateral movements of the upper body, which comprised of nearly 50% of total body mass. Consequently, this resulted in opposite movements in the rest of the segments. As shown in the ensemble curves, for the left and right trunk bending conditions, upper body COM started to move in the bending direction at Takeoff, suggesting a preparatory strategy during the jumping phase. This modification likely altered the jump strategy, as jump height was decreased in the two lateral trunk bending conditions. Participants continued to move their upper body in the bending direction and other segments in the opposite direction after Takeoff. As both legs moved opposite to the bending direction, the ipsilateral leg moved medially toward the whole body COM. Meanwhile, the contralateral leg moved laterally away from the whole body COM.

The findings support the hypothesis that the ipsilateral leg would demonstrate greater peak VGRF when landing after lateral trunk bending compared with landing without lateral trunk bending. These findings are consistent with the studies by Dempsey et al. (2012) and Yom et al. (2014), showing that lateral trunk bending increased ipsilateral leg loading. In the current study, movement was induced by self-initiated lateral trunk bending compared to an external force (Yom et al, 2014). Therefore, the current findings may be more relevant for ACL injuries not involving mid-flight external contact. The current study also differed from Dempsey et al, (2012) by observing asymmetric landing patterns when participants were allowed to land on two legs, which may represent a different sports scenario. The ipsilateral leg tended to land earlier and was closer to the whole body COM compared with the contralateral leg. These two factors may contribute to the increased peak VGRF experienced by the ipsilateral leg for the lateral trunk bending conditions. The findings suggest that mid-flight lateral trunk bending, which is integral to many sports, can lead to asymmetric landing patterns.

The findings also support the hypothesis that the ipsilateral leg would demonstrate increased knee valgus and knee internal rotation angles. However, they do not support the hypothesis that the ipsilateral leg would demonstrate decreased knee flexion angles after landing with lateral trunk bending. Lateral trunk bending persisted from Maximum Height to Landing. Increased lateral trunk bending at landing may contribute to the increased knee valgus angles at peak VGRF for the ipsilateral leg as previously described (Hewett & Myer, 2011). On the other hand, lateral trunk bending resulted in opposite changes to the contralateral leg and increased its knee varus angles at peak VGRF. In addition, knee internal rotation angles also increased for the ipsilateral leg but decreased for the contralateral leg. Previously studies have observed decreased knee flexion angles during single-leg landings compared with double-leg landings (Donohue et al., 2015; Yeow et al., 2010). In the current study, participants landed with each foot on a force platform. Although the ipsilateral leg landed earlier, the time differences on average were less than 20 ms with small effect sizes. Therefore, the changes in knee flexion angles were much less compared with solely landing on a single leg. An increased landing pattern asymmetry may produce changes in knee flexion angles more comparable to those seen in single-leg landings. In summary, the ipsilateral leg demonstrated increased impact GRF, knee abduction, and internal rotation angles at peak VGRF, which have been associated with increased ACL loading (Dai et al., 2014). These findings are consistent with a previous study, showing increased lateral trunk bending to the injured leg when ACL injuries occur (Hewett et al., 2009).

The findings may also help explain the discrepancies in ACL injury rates related to limb dominance in certain sports. In volleyball and badminton, players use their dominant arms to spike a ball or smash a shuttlecock. In badminton, of the ACL injuries that occurred during landing after an overhead stroke, 90% were to the knee opposite to the dominant arm (Kimura et al., 2010). In volleyball, of the injuries occurred during landing from a jump attack, 67% were to the knee opposite to the dominant arm (Devetag et al., 2016). A ball or shuttlecock on a player's dominant-arm side can be reached by extending the dominant shoulder and elbow. One on the non-dominant-arm side a similar distance away may require lateral trunk bending to the non-dominant-arm side. The greater mass of a trunk compared with the mass of an arm may induce greater perturbation to the body and increase landing asymmetries. In addition, lateral trunk bending to the non-dominant-arm side will elevate the height of the dominant shoulder, potentially allowing players to contact the ball or shuttlecock at a higher point. In fact, of the ACL injuries occurred during landing after an overhead stroke in badminton, most occurred in a court position that was opposite to the dominant arm (Kimura et al., 2010). When volleyball players (96% right-side dominant) landed on a single leg after a jump attack, the probabilities of landing on the left were much greater than landing on the right leg (Lobietti, Coleman, Pizzichillo, & Merni, 2010). In addition, spiking a ball set to the left side of the front court resulted in a much higher percentage of single-leg landings compared with spiking a ball set to the right side of the frontal court (Lobietti et al., 2010). In summary, badminton and volleyball players are more likely to bend their trunk to the non-dominant-arm side, which may increase the loading to the knee opposite to the dominant arm and contribute to its increased ACL injury rates.

Multiple strategies may be used to decrease the loading imposed to the ipsilateral leg associated with mid-flight lateral trunk bending. First, after completing a sports task which involves lateral trunk bending in mid-flight, individuals can try to return their trunk to an upright position, so that two legs can land at similar times and experience balanced loading.

Proprioception and core strength (Zazulak et al., 2007), common targets of ACL injury prevention programs (Brown, Palmieri-Smith, & McLean, 2014), may be important factors in the application of this strategy. Second, individuals may increase knee and hip flexion in the air to have more time to adjust their trunk position and prepare for a soft landing (Dai, Garrett et al., 2015). Third, if there is excessive lateral trunk bending and the contralateral leg is not close to the whole body COM, softly landing on the ipsilateral leg, while transitioning to a safe fall to the trunk bending direction, may be a good option. Utilization of these strategies will depend on an individual's physical capacity and performance goals as well as the demands of each specific sports situation. Previous jump-landing training has been focused on minimizing landing errors (Mandelbaum et al., 2005; Padua et al., 2012). It may also be beneficial to screen and train landing patterns with mid-flight lateral trunk bending.

Several limitations existed in the current study. First, since the lateral trunk bending was anticipated, it may not be representative of scenarios characterized by mid-flight reactions to dynamic environments. Future studies are needed to incorporate actual objects for reaching, shift of attention, and decision making to better simulate a real sports scenario. Second, the exact amount of lateral trunk bending was quantified but not controlled. Instead, participants laterally bent their trunk as far as possible while still landing with each foot on a force platform. More extreme lateral trunk bending may occur if foot placements were not constrained, but this may also raise safety concerns. Finally, the current findings do not account for differences that might exist among athletes from various sports. All participants were right-handed and tended to demonstrate greater lateral trunk bending to the left than to the right. This increased trunk bending toward the non-dominant arm might be related to previous experience.

Conclusions

Mid-flight lateral trunk bending caused movements of the pelvis and two legs in the opposite direction of the bending side and resulted in an asymmetric landing posture. The lateral trunk bending and asymmetric posture resulted in landing biomechanics associated with increased ACL loading for the ipsilateral leg. The current findings may provide additional information for understanding the role of altered trunk motion observed during ACL injury events and the discrepancy in ACL injury rates related to limb dominance in badminton and volleyball. Screening and training landing patterns following mid-flight lateral trunk bending is recommended for ACL injury prevention programs.

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Figure Captions

Figure 1. Frontal and side views of marker placement

Figure 2. Up (top) and Right Bending (bottom) conditions at different time events for the jump-landing task

Figure 3. Ensemble curves with the 95% confidence interval of the mean for lateral trunk bending angles from Takeoff to Landing for the Left Bending, Right Bending, and Up conditions.

Figure 4. Ensemble curves with the 95% confidence interval of the mean for upper body center of mass (COM) positions relative to whole body COM from Takeoff to Landing for the Left Bending, Right Bending, and Up conditions.

Figure 5. Ensemble curves with the 95% confidence interval of the mean for pelvis center of mass (COM) positions relative to whole body COM from Takeoff to Landing for the Left Bending, Right Bending, and Up conditions.

Figure 6. Ensemble curves with the 95% confidence interval of the mean for ipsilateral leg center of mass (COM) positions relative to whole body COM from Takeoff to Landing for the Left Bending, Right Bending, and Up conditions.

Figure 7. Ensemble curves with the 95% confidence interval of the mean for contralateral leg center of mass (COM) positions relative to whole body COM from Takeoff to Landing for Left Bending, Right Bending, and Up conditions.

Table 1. Definitions of anatomical landmarks, joint centers, and segment inertia parameters based on de Leva (1996)

Segments	Proximal Anatomical Landmarks	Markers to Define Proximal Anatomical Landmarks	Distal Anatomical Landmarks	Markers to Define Distal Anatomical Landmarks	Mass (% total body mass)		Center of Mass Position from Proximal to Distal Landmarks (%)	
					Females	Males	Females	Males
Head	Vertex	Vertex	Mid-Gonion	Mid-point between left and right gonions	6.68	6.94	58.94	59.76
Upper and Middle Trunk	Mid-Shoulder	Mid-point between left and right spinous process of acromioclavicular joints	Omphalion	Mid-point between left and right iliac crests	30.1	32.29	37.27	41.6
Pelvis	Omphalion	Mid-point between left and right iliac crests	Mid-Hip	Mid-point between left and right hip centers	12.47	11.17	49.20	61.15
Upper Arm	Shoulder Center	Spinous process of acromioclavicular joint	Elbow Center	Olecranon process	2.55	2.71	57.54	57.72
Fore-Arm	Elbow Center	Olecranon process	Wrist Center	Mid-point of radial and ulnar styloid processes	1.38	1.62	45.59	45.74
Hand	Wrist Center	Mid-points of radial and ulnar styloid processes	Third Metacarpal	Third metacarpal head	0.56	0.61	74.74	79.00
Thigh	Hip Center	30% distal, 14% medial, and 22% posterior of the distance between the two anterior superior iliac spines to the anterior superior iliac spine	Knee Center	Mid-point between the medial and lateral femoral condyles	14.78	14.16	36.12	40.95
Shank	Knee Center	Mid-point between the medial and lateral femoral condyles	Ankle Center	Mid-point between the medial and lateral malleoli	4.81	4.33	43.52	43.95
Foot	Heel	Heel	Tip of the Longest Toe	Tips of Big toes	1.29	1.37	40.14	44.15

Table 2. Lateral trunk bending angles and center of mass positions of the upper body, pelvis, ipsilateral leg, and contralateral leg at Takeoff, Maximum Height, and First Initial Landing

	Means (Standard Deviations)			p Values of Paired T-tests		
	Left Bending	Right Bending	Up	Left Bending vs. Right Bending	Left Bending vs. Up	Right Bending vs. Up
Lateral Trunk Bending Angle at Takeoff (°)	7.1 (3.5)	6.4(4.3)	-0.5 (1.5)	0.28	**<0.001**	**<0.001**
Upper Body COM at Takeoff (BH%)	1.4 (0.8)	1.3 (0.8	-0.1 (0.3)	0.72	**<0.001**	**<0.001**
Pelvis COM at Takeoff (BH%)	-1.4 (0.8)	-1.3 (0.9)	0.1 (0.3)	0.39	**<0.001**	**<0.001**
Ipsilateral Leg COM at Takeoff (BH%)	5.8 (1.0)	5.8 (1.0)	7.0 (0.7)	0.97	**<0.001**	**<0.001**
Contralateral Leg COM at Takeoff (BH%)	-8.1 (0.9)	-8.1 (0.9)	-6.9 (0.7)	0.77	**<0.001**	**<0.001**
Lateral Trunk Bending Angle at Maximum Height (°)	18.3 (6.7)	15.4 (6.4)	-0.9 (1.8)	**0.002**	**<0.001**	**<0.001**
Upper Body COM at Maximum Height (BH%)	3.0 (1.0)	2.7 (1.1)	-0.1 (0.4)	0.05	**<0.001**	**<0.001**
Pelvis COM at Maximum Height (BH%)	-4.5 (1.4)	-4.0 (1.4)	0.3 (0.4)	**0.001**	**<0.001**	**<0.001**
Ipsilateral Leg COM at Maximum Height	4.9 (1.4)	5.1 (1.4)	7.0 (0.8)	0.42	**<0.001**	**<0.001**
Contralateral Leg COM at Maximum Height (BH%)	-9.2 (1.5)	-8.9 (1.7)	-6.8 (0.9)	0.21	**<0.001**	**<0.001**
Lateral Trunk Bending Angle at Initial Landing (°)	17.0 (6.8)	13.9 (7.1)	-1.1 (2.2)	**0.004**	**<0.001**	**<0.001**
Upper Body COM at First Initial Landing (BH%)	3.8 (1.3)	3.3 (1.5)	-0.2 (0.5)	**0.013**	**<0.001**	**<0.001**
Pelvis COM at First Initial Landing (BH%)	-3.3 (1.2)	-2.8 (1.2)	0.3 (0.4)	**0.001**	**<0.001**	**<0.001**
Ipsilateral Leg COM at First Initial Landing (BH%)	3.8 (1.4)	4.1 (1.6)	7.0 (0.9)	0.07	**<0.001**	**<0.001**

ABSTRACT

Increased lateral trunk bending to the injured side has been observed when ACL injuries occur. The purpose was to quantify the effect of mid-flight lateral trunk bending on center of mass (COM) positions and subsequent landing mechanics during a jump-landing task. Forty-one recreational athletes performed a jump-landing task with or without mid-flight lateral trunk bending. When the left and right trunk bending conditions were compared with the no trunk bending condition, participants moved the COM of the upper body to the bending direction, while the COM of the pelvis, ipsilateral leg, and contralateral leg moved away from the bending direction relative to the whole body COM. Participants demonstrated increased peak vertical ground reaction forces (VGRF) and knee valgus and internal rotation angles at peak VGRF for the ipsilateral leg, but decreased peak VGRF and knee internal rotation angles at peak VGRF and increased knee varus angles at peak VGRF for the contralateral leg. Mid-flight lateral trunk resulted in an asymmetric landing pattern associated with increased ACL loading for the ipsilateral leg. The findings may help to understand altered trunk motion during ACL injury events and the discrepancy in ACL injuries related to limb dominance in badminton and volleyball.

Introduction

Athletes commonly suffer non-contact anterior cruciate ligament (ACL) injuries during jump-landing tasks (Devetag, Mazzilli, Benis, La Torre, & Bonato, 2016; Hewett, Torg, & Boden, 2009; Kimura et al., 2010; Stuelcken, Mellifont, Gorman, & Sayers, 2016). Small knee flexion angles and increased knee abduction and internal rotation angles along with increased anterior tibial shear forces and tibiofemoral compressive forces are associated with increased ACL loading (Dai, Mao, Garrett, & Yu, 2014). Consistently, ACL injuries typically occur during the early phase of landing when individuals demonstrate small knee flexion angles, increased knee abduction and internal rotation angles, and altered trunk angles (Dai, Mao, Garrett, & Yu, 2015; Hewett et al., 2009; Koga et al., 2010; Krosshaug et al., 2007; Stuelcken et al., 2016). Therefore, jump-landing training with a goal to decrease ACL injury risk has been focused on decreasing impact ground reaction forces, increasing knee flexion, and minimizing non-sagittal plane knee motion (Dai, Garrett et al., 2015; Welling, Benjaminse, Gokeler, & Otten, 2016).

Compared to altered knee kinematics, the relationship between altered trunk motion and increased risk for ACL injury during jump-landing remains unclear. Increased lateral trunk bending to the side of injury has been observed in conjunction with increased knee abduction during ACL injuries in female basketball and netball players (Hewett et al., 2009; Stuelcken et al., 2016). When the foot is fixed on the ground, lateral trunk bending can result in an external hip abduction moment on the bending side, which needs to be balanced by an internal hip adduction moment. Such an internal hip adduction moment may cause the knee to move medially and increase external knee abduction moments during landing (Hewett & Myer, 2011). This mechanical connection between trunk and knee motion provides a plausible explanation for the increased lateral trunk bending observed during ACL injury events. A prospective study supports the connection between trunk control and ACL injury risk by showing that female athletes with increased trunk displacements under sudden perturbation demonstrate increased risk for ACL injury (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007). Previous efforts to understand lateral trunk bending and ACL injury risk, however, have been focused on the landing phase (Hewett & Myer, 2011). Interestingly, badminton and volleyball, two sports that involve mid-flight trunk bending and reaching of the dominant arm, have shown increased ACL injury rates to the knee opposite to the dominant arm after landing (Devetag et al., 2016; Kimura et al., 2010). Quantifying how trunk motion prior to landing may affect landing biomechanics can provide additional information for understanding the relationship between lateral trunk bending and ACL injury risk.

Relatively few studies have quantified the effect of mid-flight trunk motion on landing mechanics (Dempsey, Elliott, Munro, Steele, & Lloyd, 2012; Yom, Simpson, Arnett, & Brown, 2014). Dempsey et al. (2012) found that landing after catching a ball that was lateral to the landing leg increased peak knee valgus moments compared with landing after catching a ball medial to the landing leg. The participants in this study, however, were instructed to land with a single leg on a force platform. Single-leg landings result in changes in lower extremity biomechanics that are associated with greater ACL loading compared with double-leg landing (Donohue et al., 2015; Yeow, Lee, & Goh, 2010). Whether participants would unintentionally adopt a single-leg landing after mid-flight trunk motion remains unknown. Yom et al. (2014) demonstrated that landing after mid-flight trunk perturbation induced by an external pulling force resulted in increased peak ground reaction forces, increased knee abduction angles, and decreased knee flexion angles for the leg on the same side of the pulling force. A pulling force simulates ACL injuries that involve mid-flight contact with other players, and whether this contact contributes to the injury situation warrants future investigation. However, this method of trunk perturbation may not represent other ACL injury scenarios, during which individuals have no mid-flight contact with other players.

Athletes commonly perform self-initiated mid-flight lateral trunk bending during sports competition (Kimura et al., 2010). Mid-flight lateral trunk bending may cause re-positioning of segmental centers of mass (COM) and affect landing mechanics. Newton's laws indicate that an individual's whole body COM in the air will demonstrate a parabola shaped trajectory when air resistance is negligible. Therefore, when specific body segments move in one direction relative to the whole body COM in mid-flight, some other segments must move in the opposite direction.

The purpose of the current study was to quantify the effect of mid-flight lateral trunk bending on COM positions and subsequent landing mechanics during a jump-landing task. It was hypothesized that lateral trunk bending in one direction would cause leg movements in the opposite direction. Consequently, the ipsilateral leg would be displaced closer to the whole body COM, while the contralateral leg would be displaced further away from the whole body COM in the mediolateral direction. Based on the literature (Dempsey et al., 2012; Yom et al., 2014), it was also hypothesized that the ipsilateral leg would experience increased peak vertical ground reaction forces (VGRF), decreased knee flexion angles at peak VGRF, and increased knee valgus and internal rotation angles at peak VGRF when landing after mid-flight lateral trunk bending compared with landing without mid-flight lateral trunk bending.

Methods

Participants

Based on previous studies which quantified the effect of mid-flight trunk motion or perturbation on landing biomechanics (Dempsey et al., 2012; Yom et al., 2014), a medium to large effect size was expected for the current study. Assuming a medium effect size of 0.5 for a paired t-test, a sample size of 34 was needed for a type I error at the level of 0.05 to achieve a power of 0.8. Forty-one participants were recruited (sex: 18 males, 23 females; age: 22.0 ± 3.0 years; height: 1.74 ± 0.10 m; mass: 71.0 ± 13.9 kg). All participants preferred to use the right arm to throw a football for further distance. Twenty-eight of them preferred to jump off the right leg for a further distance. Participants had experience with sports that involved jump-landing tasks and participated in sports or exercise at least two times for a total of two to three hours per week at the time of testing. Exclusion criteria were described in a previous study (Dai, Garrett et al., 2015). This study was approved by XXX Institutional Review Board. Participants signed informed consent forms and completed a questionnaire to screen for exclusion criteria prior to data collection.

Procedures

Participants wore a baseball cap, spandex pants, a spandex shirt, and standard athletic shoes (Ghost 5, Brooks Sports Inc. Seattle, WA, USA). Participants completed a standard warm-up including five minutes of running at a self-selected speed on a treadmill and a dynamic stretching protocol. Retroreflective markers were placed on a participant's vertex, gonions, sternum, acromioclavicular joints, olecranon processes, mid-points of radial and ulnar styloid processes, third metacarpal heads, anterior superior iliac spines, posterior superior iliac spines, iliac crests, greater trochanters, lateral thighs, anterior thighs, medial and lateral femoral condyles, superior and inferior shanks, lateral shanks, medial and lateral malleolus, tips of big toes, heels, and the fifth metatarsal heads (Figure 1).

Figure 1 near here

After a static trial, participants performed a vertical counter-movement jump-landing task with or without lateral trunk bending. The jump-landing task was designed to simulate basketball rebounding and volleyball blocking, during which athletes laterally bend their trunk and reach both hands to catch or block a ball. This task also had implication for volleyball spiking and badminton smashing, both of which involved lateral trunk bending and one hand reaching. Participants started with feet shoulder-width apart and one foot on each of the two force platforms. In the Up condition, participants were instructed to jump for maximum height and reach both hands in the up direction without laterally bending their trunk (Figure 2). In the Right Bending or Left Bending condition, participants were instructed to jump for maximum height and bend their trunk to the right or left as far as they could and reach both hands to the right or left when they reach their maximum height (Figure 2). In all three conditions, participants were instructed to land with one foot on each of the two force platforms. A trial was repeated if participants did not land on targeted force platforms. No other instruction regarding body movements or landing techniques was given. Participants practiced each jump-landing task for a minimum of two trials, followed by three official trials. Participants were given a minimum of 30-second rest between trials. The order of the three jump-landing tasks was randomized for each participant.

Figure 2 near here

The three-dimensional positions of retroreflective markers were tracked using eight Vicon Bonita cameras at a sampling frequency of 160 Hz (Vicon Motion Systems Ltd, Oxford, UK). Ground reaction forces were recorded using two Bertec FP4060-10 force platforms at a sampling frequency of 1600 Hz (Bertec Corporation, Columbus, OH, USA). Kinematic and ground reaction force data were collected using Vicon Nexus 1.8.2 software (Vicon Motion Systems Ltd, Oxford, UK).

Data Reduction

Kinematic and ground reaction force data were filtered using fourth-order Butterworth low-pass filters at 15 Hz and 100 Hz, respectively (Dai et al., 2016). Markers placed on the pelvis and lower extremities were calibrated during the static trial and reconstructed during the jump-landing trials using a singular decomposition method (Soderkvist & Wedin, 1993). The hip joint was defined as a fixed point in the pelvis reference frame (Bell, Brand, & Pedersen, 1989). Other joints were defined as described in Table 1. The mass and COM locations of each segment were determined based on the literature (de Leva, 1996). The segmentation method (Hay, 1993) was used to calculate the COM of the whole body and four other major components: the upper body including all segments above the pelvis, the pelvis, and two legs ipsilateral or contralateral to the bending side. Cardan angles with an order of rotation of flexion-extension, right-left lateral bending, and left-right axial rotation were calculated between the global and upper-middle trunk reference frames to quantify trunk angles. Similarly, knee joint angles were calculated as the Cardan angles with an order of rotation of flexion-extension, varus-valgus, and internal-external rotation between the thigh and shank reference frames. Knee joint angles during the static trials were defined as the neutral alignment and subtracted from the angles during jump-landing trials.

Table 1 near here

Takeoff was defined as the first time event when both feet were off the force platforms. Maximum Height was defined as the time event when the whole body COM reached maximum height. First Initial Landing was defined as the time event when the first foot landed on a force platform. Second Initial Landing was defined as the time event when the second foot landed on a force platform. The lateral trunk bending angles and COM of the upper body, pelvis, ipsilateral leg, and contralateral leg positions relative to the whole body COM in the mediolateral direction was calculated at Takeoff, Maximum Height, and First Initial Landing. For the Left Bending and Right Bending conditions, the direction of the bending side was defined as positive. For the Up condition, the right direction was defined as positive and the right leg was the ipsilateral leg. COM positions were normalized as a percentage of the participants' body height.

Time differences between the First and Second Initial Landing were calculated with landing of the ipsilateral leg prior to the contralateral leg defined as positive. ACL injuries typically occur during the first 100 ms after initial contact (Dai et al., 2014). In addition, increased impact GRF, knee valgus and internal rotation angles as well as decreased knee flexion angles are associated with increased ACL loading (Dai et al., 2014). Therefore, the peak VGRF during the first 100 ms after initial landing was quantified for each leg. Knee flexion, valgus, and internal rotation angles at the peak VGRF were extracted for each leg. VGRF was normalized to the participants' body weight. Jump height was calculated relative to the whole body COM during static trials and jump-landing trials to quantify jump performance. Calculations were performed using customized subroutines developed in MATLAB 2016b (MathWorks Inc. Natick, MA).

Statistical Analysis

Data for the three official trials for each jump-landing condition for each participant were averaged for analysis. COM positions, lower extremity kinematic and kinetic variables, and jump height were compared among the three jump-landing conditions using repeated measures analyses of variance (ANOVA). When an ANOVA showed a significant main effect, paired t-tests were performed between each pair of two jump-landing conditions. A type-I error rate was set at 0.05 for the ANOVAs for statistical significance. A procedure was applied to all paired t-tests to control the study-wide false discovery rate at 0.05 (Benjamini & Hochberg, 1995). Cohen's dz was calculated to evaluate the effect size of changes in jump height and landing variables between two jump-landing conditions with Cohen's dz ≥ 0.8 considered "large," $0.5 <$ Cohen's dz < 0.8 considered "medium," and Cohen's dz < 0.5 considered "small" (Cohen, 1988). Statistical analyses were performed using SPSS Statistics 24 software (IBM Corporation, Armonk, NY, USA).

Results

ANOVAs showed significant main effects ($p < 0.05$) for all variables except for knee flexion angles at peak VGRF for both ipsilateral and contralateral legs. A total of 69 paired t-tests were performed for the other 23 variables, and the largest p value for a significant paired t-test was 0.026 after the adjustment for the false discovery rate.

When the Left Bending and Right Bending conditions were compared with the Up condition, participants significantly increased lateral trunk bending (Figure 3) and moved the COM of the upper body (Figure 4) to the bending direction relative to the whole body COM, while the COM of the pelvis (Figure 5), ipsilateral leg (Figure 6), and contralateral leg (Figure 7) moved away from the bending direction relative to the whole body COM from Takeoff to First Initial Landing (Table 2). Some significant differences were also observed between the Left Bending and Right Bending conditions.

Jump height significantly decreased for the Left Bending and Right Bending conditions compared with the Up condition with large effect sizes (Table 3). Participants landed on the ipsilateral leg significantly earlier for the Left Bending condition compared with the Up condition, while a similar trend was observed for the Right Bending condition. The effect sizes for time differences were small. When the Left Bending and Right Bending conditions were compared with the Up condition, participants demonstrated increased peak VGRF and knee valgus and internal rotation angles at peak VGRF for the ipsilateral leg but decreased peak VGRF and knee internal rotation angles at peak VGRF and increased knee varus angles at peak VGRF for the contralateral leg with mostly medium to large effect sizes.

Tables 2-3 near here

Figures 3-7 near here

Discussion

The purpose of the current study was to quantify the effect of mid-flight lateral trunk bending on COM positions and subsequent landing mechanics during a jump-landing task. The findings support the hypothesis that mid-flight lateral trunk bending in one direction would cause leg movements in the opposite direction. Since participants jumped vertically, the mid-flight trajectory of the whole body COM should be close to a straight line. Lateral trunk bending was characterized by lateral movements of the upper body, which comprised of nearly 50% of total body mass. Consequently, this resulted in opposite movements in the rest of the segments. As shown in the ensemble curves, for the left and right trunk bending conditions, upper body COM started to move in the bending direction at Takeoff, suggesting a preparatory strategy during the jumping phase. This modification likely altered the jump strategy, as jump height was decreased in the two lateral trunk bending conditions. Participants continued to move their upper body in the bending direction and other segments in the opposite direction after Takeoff. As both legs moved opposite to the bending direction, the ipsilateral leg moved medially toward the whole body COM. Meanwhile, the contralateral leg moved laterally away from the whole body COM.

The findings support the hypothesis that the ipsilateral leg would demonstrate greater peak VGRF when landing after lateral trunk bending compared with landing without lateral trunk bending. These findings are consistent with the studies by Dempsey et al. (2012) and Yom et al. (2014), showing that lateral trunk bending increased ipsilateral leg loading. In the current study, movement was induced by self-initiated lateral trunk bending compared to an external force (Yom et al, 2014). Therefore, the current findings may be more relevant for ACL injuries not involving mid-flight external contact. The current study also differed from Dempsey et al, (2012) by observing asymmetric landing patterns when participants were allowed to land on two legs, which may represent a different sports scenario. The ipsilateral leg tended to land earlier and was closer to the whole body COM compared with the contralateral leg. These two factors may contribute to the increased peak VGRF experienced by the ipsilateral leg for the lateral trunk bending conditions. The findings suggest that mid-flight lateral trunk bending, which is integral to many sports, can lead to asymmetric landing patterns.

The findings also support the hypothesis that the ipsilateral leg would demonstrate increased knee valgus and knee internal rotation angles. However, they do not support the hypothesis that the ipsilateral leg would demonstrate decreased knee flexion angles after landing with lateral trunk bending. Lateral trunk bending persisted from Maximum Height to Landing. Increased lateral trunk bending at landing may contribute to the increased knee valgus angles at peak VGRF for the ipsilateral leg as previously described (Hewett & Myer, 2011). On the other hand, lateral trunk bending resulted in opposite changes to the contralateral leg and increased its knee varus angles at peak VGRF. In addition, knee internal rotation angles also increased for the ipsilateral leg but decreased for the contralateral leg. Previously studies have observed decreased knee flexion angles during single-leg landings compared with double-leg landings (Donohue et al., 2015; Yeow et al., 2010). In the current study, participants landed with each foot on a force platform. Although the ipsilateral leg landed earlier, the time differences on average were less than 20 ms with small effect sizes. Therefore, the changes in knee flexion angles were much less compared with solely landing on a single leg. An increased landing pattern asymmetry may produce changes in knee flexion angles more comparable to those seen in single-leg landings. In summary, the ipsilateral leg demonstrated increased impact GRF, knee abduction, and internal rotation angles at peak VGRF, which have been associated with increased ACL loading (Dai et al., 2014). These findings are consistent with a previous study, showing increased lateral trunk bending to the injured leg when ACL injuries occur (Hewett et al., 2009).

The findings may also help explain the discrepancies in ACL injury rates related to limb dominance in certain sports. In volleyball and badminton, players use their dominant arms to spike a ball or smash a shuttlecock. In badminton, of the ACL injuries that occurred during landing after an overhead stroke, 90% were to the knee opposite to the dominant arm (Kimura et al., 2010). In volleyball, of the injuries occurred during landing from a jump attack, 67% were to the knee opposite to the dominant arm (Devetag et al., 2016). A ball or shuttlecock on a player's dominant-arm side can be reached by extending the dominant shoulder and elbow. One on the non-dominant-arm side a similar distance away may require lateral trunk bending to the non-dominant-arm side. The greater mass of a trunk compared with the mass of an arm may induce greater perturbation to the body and increase landing asymmetries. In addition, lateral trunk bending to the non-dominant-arm side will elevate the height of the dominant shoulder, potentially allowing players to contact the ball or shuttlecock at a higher point. In fact, of the ACL injuries occurred during landing after an overhead stroke in badminton, most occurred in a court position that was opposite to the dominant arm (Kimura et al., 2010). When volleyball players (96% right-side dominant) landed on a single leg after a jump attack, the probabilities of landing on the left were much greater than landing on the right leg (Lobietti, Coleman, Pizzichillo, & Merni, 2010). In addition, spiking a ball set to the left side of the front court resulted in a much higher percentage of single-leg landings compared with spiking a ball set to the right side of the frontal court (Lobietti et al., 2010). In summary, badminton and volleyball players are more likely to bend their trunk to the non-dominant-arm side, which may increase the loading to the knee opposite to the dominant arm and contribute to its increased ACL injury rates.

Multiple strategies may be used to decrease the loading imposed to the ipsilateral leg associated with mid-flight lateral trunk bending. First, after completing a sports task which involves lateral trunk bending in mid-flight, individuals can try to return their trunk to an upright position, so that two legs can land at similar times and experience balanced loading.

Proprioception and core strength (Zazulak et al., 2007), common targets of ACL injury prevention programs (Brown, Palmieri-Smith, & McLean, 2014), may be important factors in the application of this strategy. Second, individuals may increase knee and hip flexion in the air to have more time to adjust their trunk position and prepare for a soft landing (Dai, Garrett et al., 2015). Third, if there is excessive lateral trunk bending and the contralateral leg is not close to the whole body COM, softly landing on the ipsilateral leg, while transitioning to a safe fall to the trunk bending direction, may be a good option. Utilization of these strategies will depend on an individual's physical capacity and performance goals as well as the demands of each specific sports situation. Previous jump-landing training has been focused on minimizing landing errors (Mandelbaum et al., 2005; Padua et al., 2012). It may also be beneficial to screen and train landing patterns with mid-flight lateral trunk bending.

Several limitations existed in the current study. First, since the lateral trunk bending was anticipated, it may not be representative of scenarios characterized by mid-flight reactions to dynamic environments. Future studies are needed to incorporate actual objects for reaching, shift of attention, and decision making to better simulate a real sports scenario. Second, the exact amount of lateral trunk bending was quantified but not controlled. Instead, participants laterally bent their trunk as far as possible while still landing with each foot on a force platform. More extreme lateral trunk bending may occur if foot placements were not constrained, but this may also raise safety concerns. Finally, the current findings do not account for differences that might exist among athletes from various sports. All participants were right-handed and tended to demonstrate greater lateral trunk bending to the left than to the right. This increased trunk bending toward the non-dominant arm might be related to previous experience.

Conclusions

Mid-flight lateral trunk bending caused movements of the pelvis and two legs in the opposite direction of the bending side and resulted in an asymmetric landing posture. The lateral trunk bending and asymmetric posture resulted in landing biomechanics associated with increased ACL loading for the ipsilateral leg. The current findings may provide additional information for understanding the role of altered trunk motion observed during ACL injury events and the discrepancy in ACL injury rates related to limb dominance in badminton and volleyball. Screening and training landing patterns following mid-flight lateral trunk bending is recommended for ACL injury prevention programs.

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Figure Captions

Figure 1. Frontal and side views of marker placement

Figure 2. Up (top) and Right Bending (bottom) conditions at different time events for the jump-landing task

Figure 3. Ensemble curves with the 95% confidence interval of the mean for lateral trunk bending angles from Takeoff to Landing for the Left Bending, Right Bending, and Up conditions.

Figure 4. Ensemble curves with the 95% confidence interval of the mean for upper body center of mass (COM) positions relative to whole body COM from Takeoff to Landing for the Left Bending, Right Bending, and Up conditions.

Figure 5. Ensemble curves with the 95% confidence interval of the mean for pelvis center of mass (COM) positions relative to whole body COM from Takeoff to Landing for the Left Bending, Right Bending, and Up conditions.

Figure 6. Ensemble curves with the 95% confidence interval of the mean for ipsilateral leg center of mass (COM) positions relative to whole body COM from Takeoff to Landing for the Left Bending, Right Bending, and Up conditions.

Figure 7. Ensemble curves with the 95% confidence interval of the mean for contralateral leg center of mass (COM) positions relative to whole body COM from Takeoff to Landing for Left Bending, Right Bending, and Up conditions.

Table 1. Definitions of anatomical landmarks, joint centers, and segment inertia parameters based on de Leva (1996)

Segments	Proximal Anatomical Landmarks	Markers to Define Proximal Anatomical Landmarks	Distal Anatomical Landmarks	Markers to Define Distal Anatomical Landmarks	Mass (% total body mass)		Center of Mass Position from Proximal to Distal Landmarks (%)	
					Females	Males	Females	Males
Head	Vertex	Vertex	Mid-Gonion	Mid-point between left and right gonions	6.68	6.94	58.94	59.76
Upper and Middle Trunk	Mid-Shoulder	Mid-point between left and right spinous process of acromioclavicular joints	Omphalion	Mid-point between left and right iliac crests	30.1	32.29	37.27	41.6
Pelvis	Omphalion	Mid-point between left and right iliac crests	Mid-Hip	Mid-point between left and right hip centers	12.47	11.17	49.20	61.15
Upper Arm	Shoulder Center	Spinous process of acromioclavicular joint	Elbow Center	Olecranon process	2.55	2.71	57.54	57.72
Fore-Arm	Elbow Center	Olecranon process	Wrist Center	Mid-point of radial and ulnar styloid processes	1.38	1.62	45.59	45.74
Hand	Wrist Center	Mid-points of radial and ulnar styloid processes	Third Metacarpal	Third metacarpal head	0.56	0.61	74.74	79.00
Thigh	Hip Center	30% distal, 14% medial, and 22% posterior of the distance between the two anterior superior iliac spines to the anterior superior iliac spine	Knee Center	Mid-point between the medial and lateral femoral condyles	14.78	14.16	36.12	40.95
Shank	Knee Center	Mid-point between the medial and lateral femoral condyles	Ankle Center	Mid-point between the medial and lateral malleoli	4.81	4.33	43.52	43.95
Foot	Heel	Heel	Tip of the Longest Toe	Tips of Big toes	1.29	1.37	40.14	44.15

Table 2. Lateral trunk bending angles and center of mass positions of the upper body, pelvis, ipsilateral leg, and contralateral leg at Takeoff, Maximum Height, and First Initial Landing

	Means (Standard Deviations)			p Values of Paired T-tests		
	Left Bending	Right Bending	Up	Left Bending vs. Right Bending	Left Bending vs. Up	Right Bending vs. Up
Lateral Trunk Bending Angle at Takeoff (°)	7.1 (3.5)	6.4(4.3)	-0.5 (1.5)	0.28	**<0.001**	**<0.001**
Upper Body COM at Takeoff (BH%)	1.4 (0.8)	1.3 (0.8	-0.1 (0.3)	0.72	**<0.001**	**<0.001**
Pelvis COM at Takeoff (BH%)	-1.4 (0.8)	-1.3 (0.9)	0.1 (0.3)	0.39	**<0.001**	**<0.001**
Ipsilateral Leg COM at Takeoff (BH%)	5.8 (1.0)	5.8 (1.0)	7.0 (0.7)	0.97	**<0.001**	**<0.001**
Contralateral Leg COM at Takeoff (BH%)	-8.1 (0.9)	-8.1 (0.9)	-6.9 (0.7)	0.77	**<0.001**	**<0.001**
Lateral Trunk Bending Angle at Maximum Height (°)	18.3 (6.7)	15.4 (6.4)	-0.9 (1.8)	**0.002**	**<0.001**	**<0.001**
Upper Body COM at Maximum Height (BH%)	3.0 (1.0)	2.7 (1.1)	-0.1 (0.4)	0.05	**<0.001**	**<0.001**
Pelvis COM at Maximum Height (BH%)	-4.5 (1.4)	-4.0 (1.4)	0.3 (0.4)	**0.001**	**<0.001**	**<0.001**
Ipsilateral Leg COM at Maximum Height	4.9 (1.4)	5.1 (1.4)	7.0 (0.8)	0.42	**<0.001**	**<0.001**
Contralateral Leg COM at Maximum Height (BH%)	-9.2 (1.5)	-8.9 (1.7)	-6.8 (0.9)	0.21	**<0.001**	**<0.001**
Lateral Trunk Bending Angle at Initial Landing (°)	17.0 (6.8)	13.9 (7.1)	-1.1 (2.2)	**0.004**	**<0.001**	**<0.001**
Upper Body COM at First Initial Landing (BH%)	3.8 (1.3)	3.3 (1.5)	-0.2 (0.5)	**0.013**	**<0.001**	**<0.001**
Pelvis COM at First Initial Landing (BH%)	-3.3 (1.2)	-2.8 (1.2)	0.3 (0.4)	**0.001**	**<0.001**	**<0.001**
Ipsilateral Leg COM at First Initial Landing (BH%)	3.8 (1.4)	4.1 (1.6)	7.0 (0.9)	0.07	**<0.001**	**<0.001**

Contralateral Leg COM at First Initial Landing (BH%)	-10.7 (1.8)	-10.1 (1.9)	-6.7 (0.8)	**0.026**	**<0.001**	**<0.001**

Note: COM: center of mass; BH: body height; Center of mass of each component was calculated relative to the total body center of mass in the mediolateral direction; For the Left Bending and Right Bending conditions, the direction of the bending side was defined as positive; For the Up condition, the right direction was defined as positive and the right leg was utilized as the ipsilateral leg.

Table 3. Jump height and kinematic and kinetic variables during landing

	Means (Standard Deviations)			Cohen's dz (p Values of Paired T-tests)		
	Left Bending	Right Bending	Up	Left Bending vs. Right Bending	Left Bending vs. Up	Right Bending vs. Up
Jump Height (m)	0.45 (0.11)	0.45 (0.11)	0.48 (0.12)	0.17 (0.28)	**1.02 (<0.001)**	**1.08 (<0.001)**
Timing Differences between First and Second Initial Contacts (ms)	14.0 (27.0)	16.7 (42.8)	2.6 (5.2)	0.10 (0.54)	**0.40 (0.014)**	0.33 (0.038)
Ipsilateral Leg Peak VGRF (BW)	2.6 (1.0)	2.6 (0.9)	2.3 (0.8)	0.08 (0.61)	**0.43 (0.008)**	**0.65 (<0.001)**
Contralateral Leg Peak VGRF (BW)	1.7 (0.7)	1.7 (0.6)	2.1 (0.7)	0.12 (0.46)	**0.55 (0.001)**	**0.64 (<0.001)**
Ipsilateral Leg Knee Flexion Angle at Peak VGRF (°)	43.3 (9.3)	42.7 (10.0)	44.6 (9.9)	0.08 (---)	0.18 (---)	0.25 (---)
Contralateral Leg Knee Flexion Angle at Peak VGRF (°)	45.5 (11.9)	43.8 (12.3)	47.1 (9.7)	0.17 (---)	0.17 (---)	0.34 (---)
Ipsilateral Knee Varus (+) / Valgus (-) Angle at Peak VGRF (°)	-3.6 (6.3)	-3.1 (5.5)	1.8 (4.8)	0.09 (0.59)	**0.82 (<0.001)**	**1.31 (<0.001)**
Contralateral Knee Varus (+) / Valgus (-) Angle at Peak VGRF (°)	5.7 (5.9)	6.0 (6.5)	0.7 (6.8)	0.05 (0.77)	**0.71 (<0.001)**	**1.51 (<0.001)**
Ipsilateral Knee Internal (+) / External (-) Rotation Angle at Peak VGRF (°)	7.3 (6.2)	6.6 (5.0)	4.2 (5.7)	0.12 (0.45)	**0.46 (0.005)**	**0.59 (<0.001)**
Contralateral Knee Internal (+) / External (-) Rotation Angle at Peak VGRF (°)	1.7 (6.9)	1.8 (6.2)	5.5 (6.2)	0.02 (0.89)	**0.56 (0.001)**	**1.09 (<0.001)**

Note: VGRF: vertical ground reaction force; BW: body weight; For Timing Differences between Two Initial Contacts, a positive number indicates the ipsilateral leg landed earlier.

Figure 1

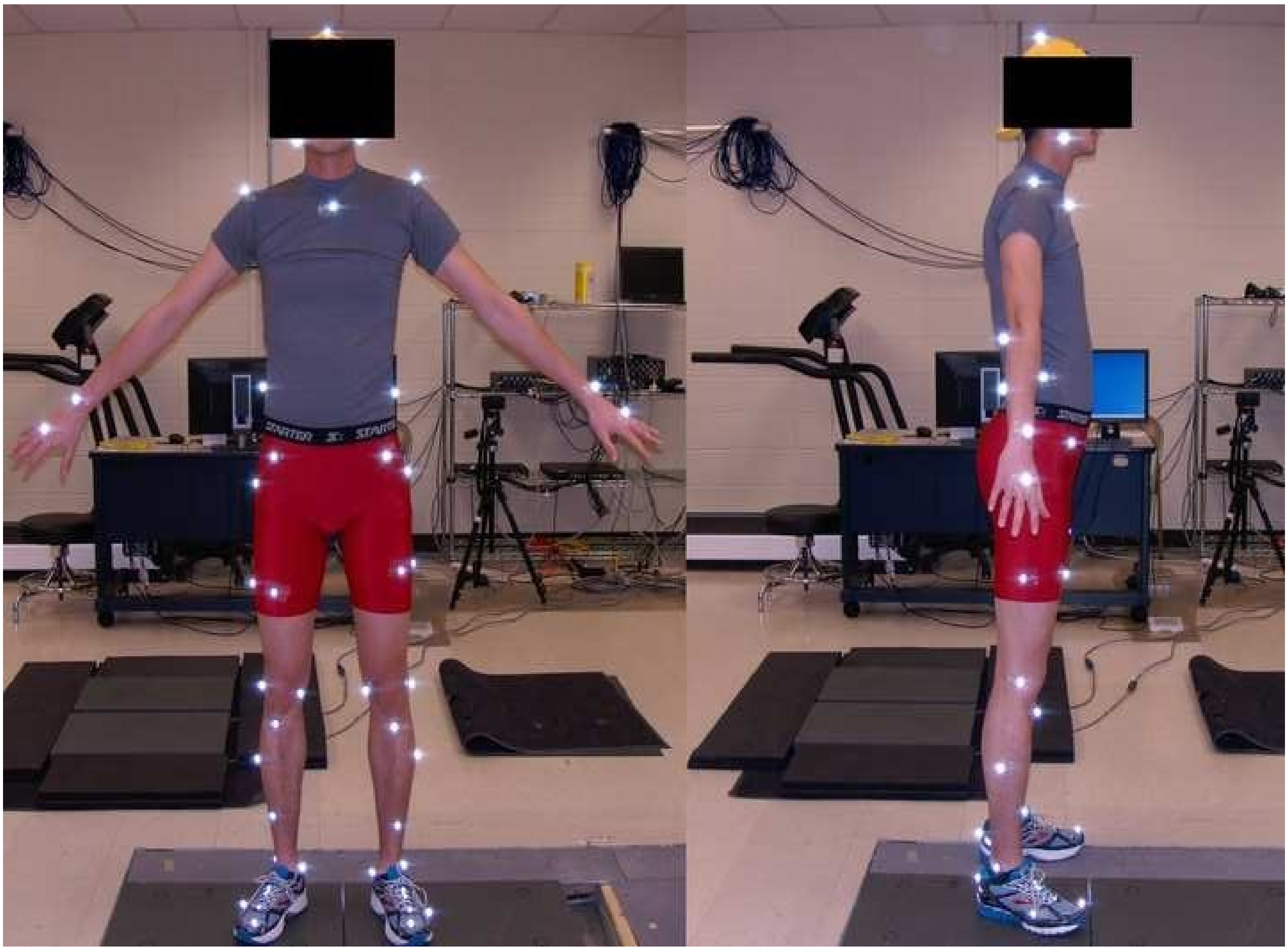


Figure 2

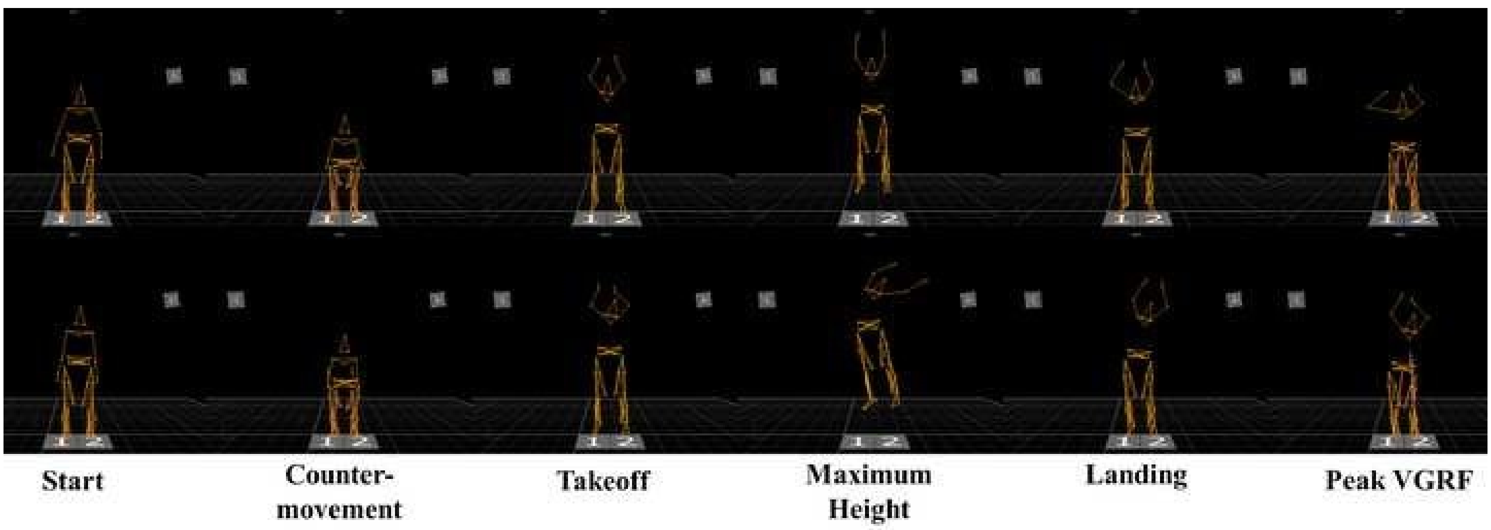
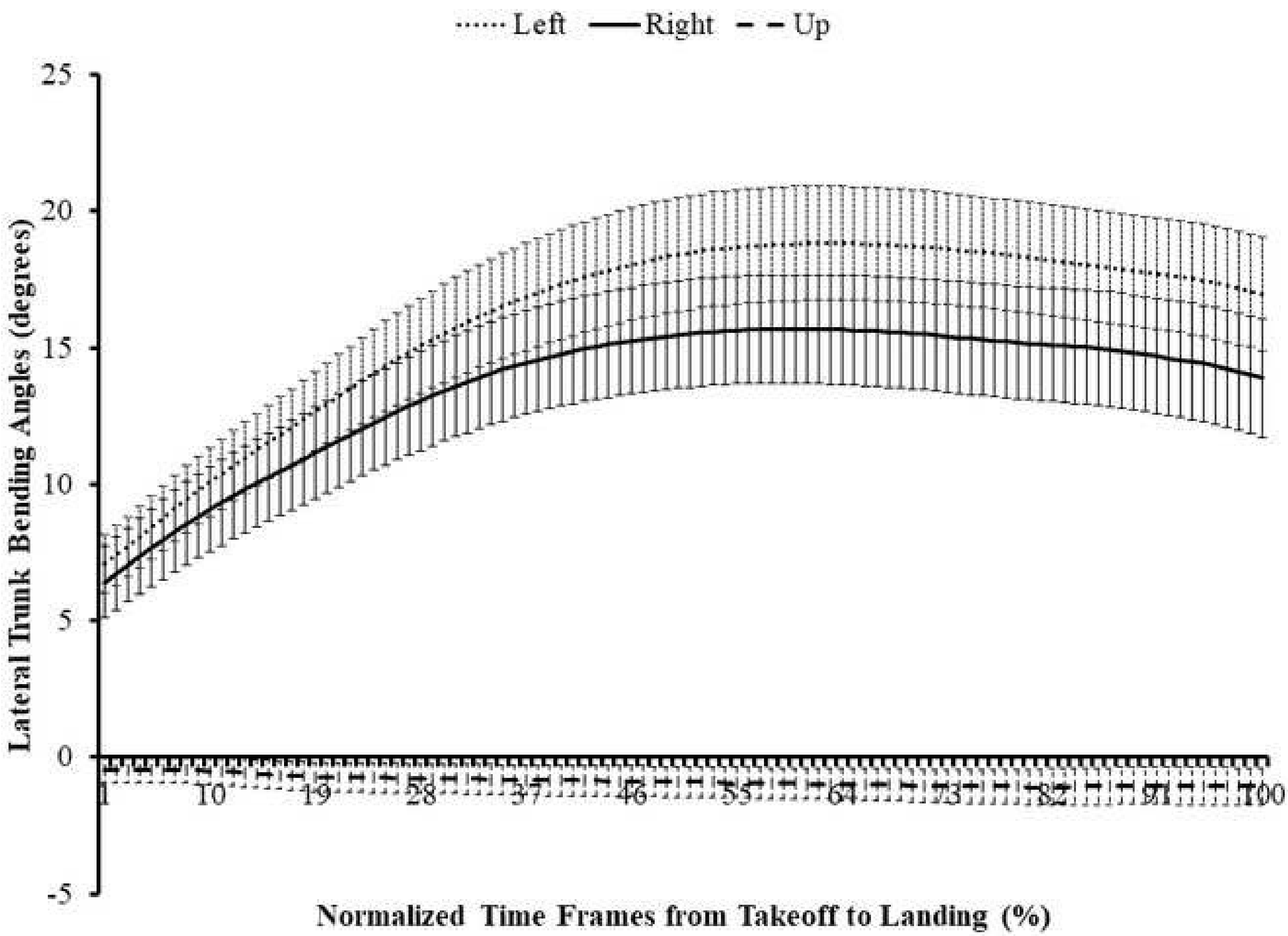
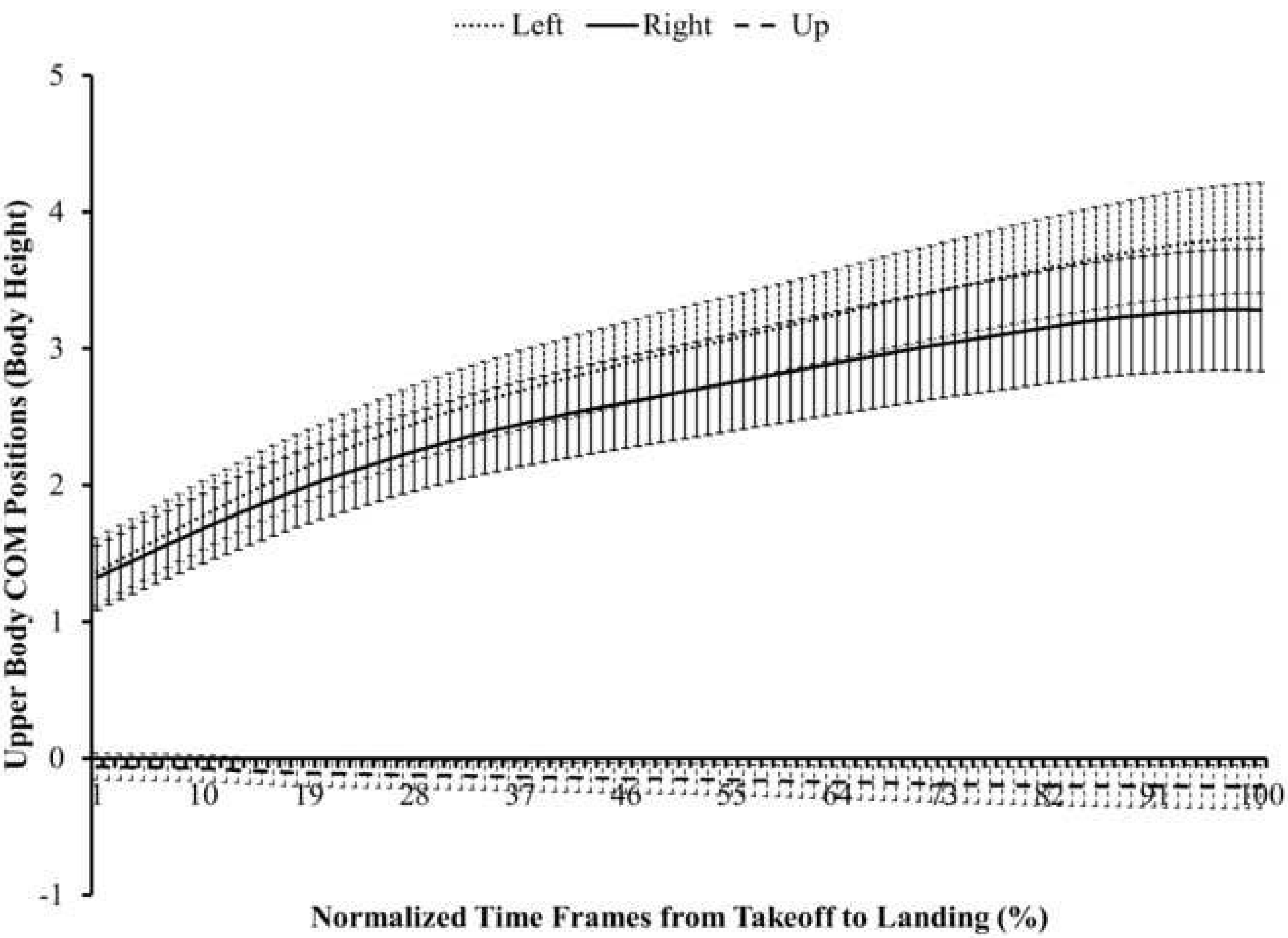

Start
Counter-movement
Takeoff
Maximum Height
Landing
Peak VGRF

Figure 3



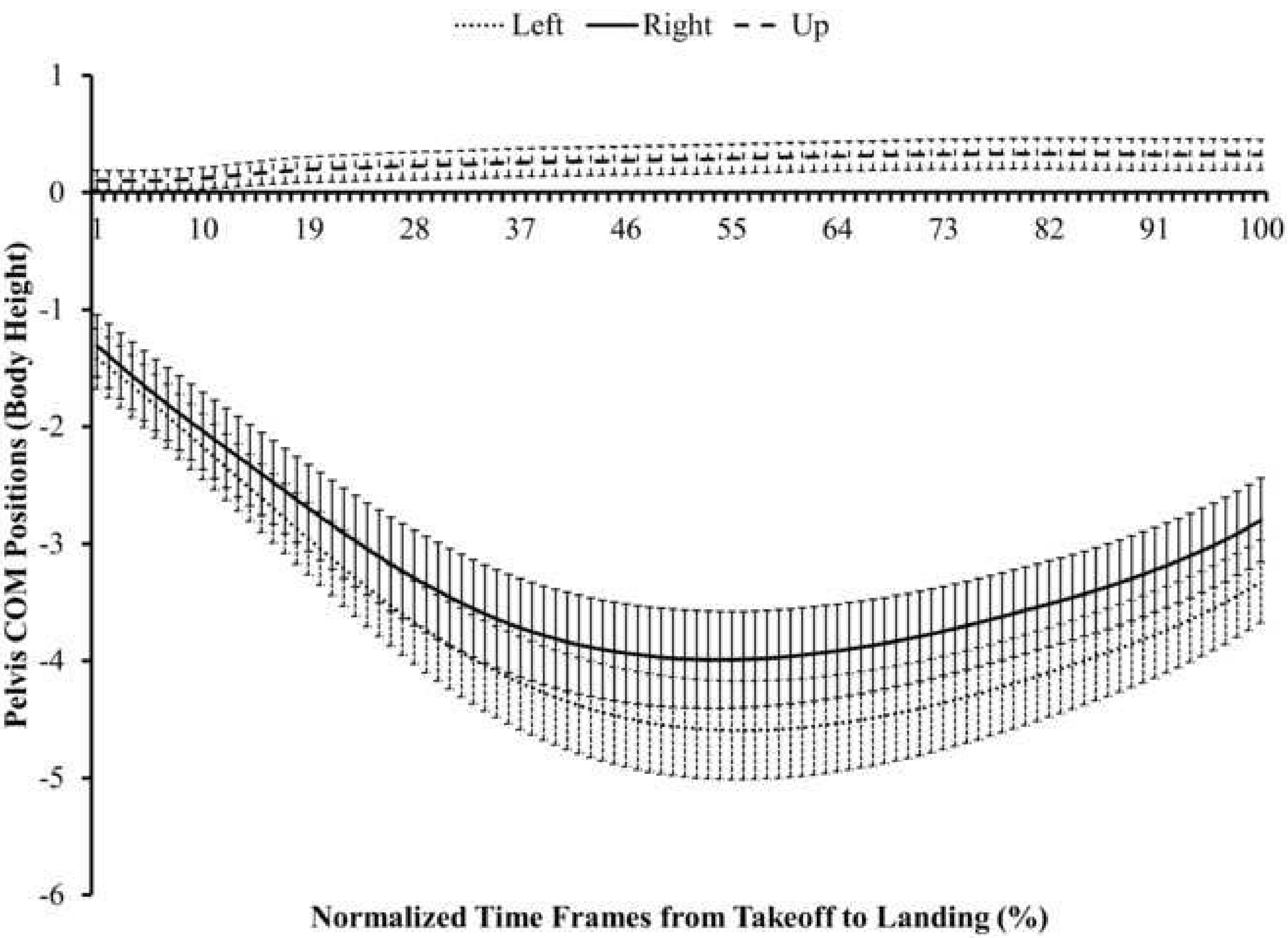
Left
Right
Up
25
20
15
10
5
0
-5
Lateral Trunk Bending Angles (degrees)
1
10
19
28
37
46
55
64
73
82
91
100
Normalized Time Frames from Takeoff to Landing (%)

Figure 4



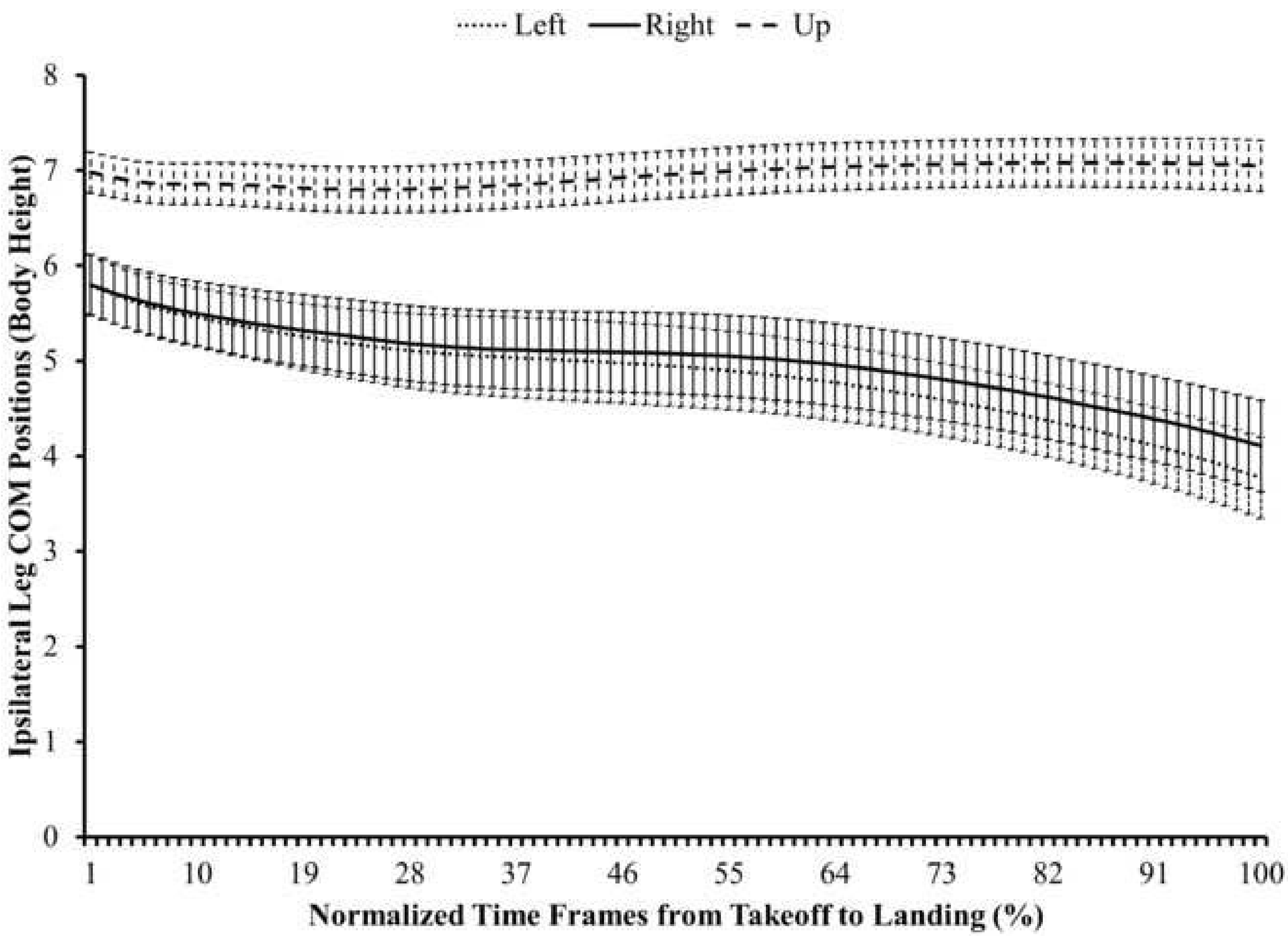
Left
Right
Up
5
4
3
2
1
0
-1
1
10
19
28
37
46
55
64
73
82
91
100
Upper Body COM Positions (Body Height)
Normalized Time Frames from Takeoff to Landing (%)

Figure 5



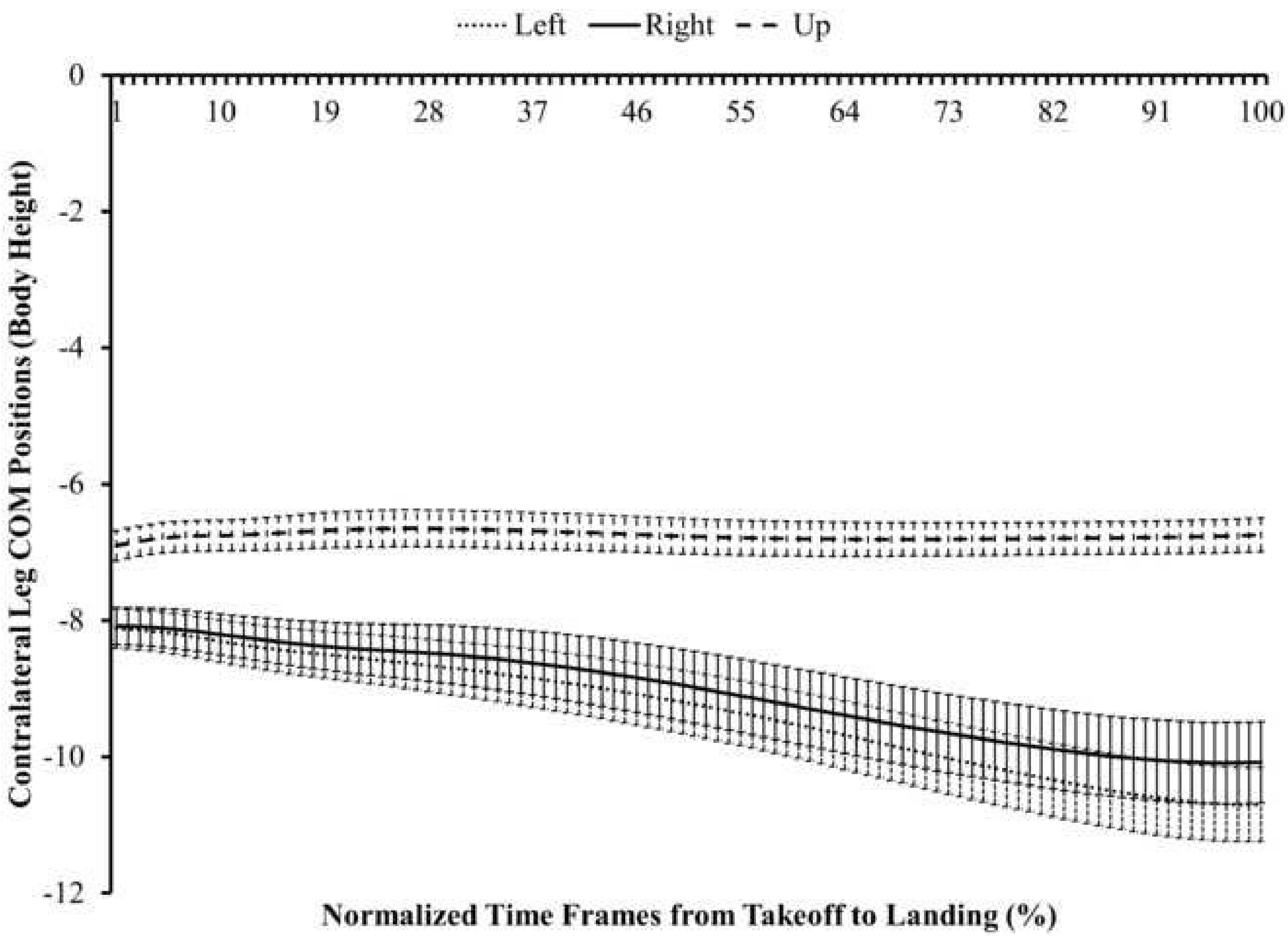
Left
Right
Up
1
0
-1
-2
-3
-4
-5
-6
1
10
19
28
37
46
55
64
73
82
91
100
Pelvis COM Positions (Body Height)
Normalized Time Frames from Takeoff to Landing (%)

Figure 6



Left
Right
Up
8
7
6
5
4
3
2
1
0
Ipsilateral Leg COM Positions (Body Height)
1
10
19
28
37
46
55
64
73
82
91
100
Normalized Time Frames from Takeoff to Landing (%)

Figure 7


Left Right Up
0
-2
-4
-6
-8
-10
-12
1 10 19 28 37 46 55 64 73 82 91 100
Contralateral Leg COM Positions (Body Height)
Normalized Time Frames from Takeoff to Landing (%)