

1 **1 Mid-flight Lateral Trunk Bending Increased Ipsilateral Leg Loading during Landing: a**

2 **2 Center of Mass Analysis**

3 **3 Running title: Lateral Trunk Bending and Landing**

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18

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

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4 **ABSTRACT**
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7 Increased lateral trunk bending to the injured side has been observed when ACL injuries occur.
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9 The purpose was to quantify the effect of mid-flight lateral trunk bending on center of mass
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11 (COM) positions and subsequent landing mechanics during a jump-landing task. Forty-one
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13 recreational athletes performed a jump-landing task with or without mid-flight lateral trunk
14
15 bending. When the left and right trunk bending conditions were compared with the no trunk
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17 bending condition, participants moved the COM of the upper body to the bending direction,
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19 while the COM of the pelvis, ipsilateral leg, and contralateral leg moved away from the bending
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21 direction relative to the whole body COM. Participants demonstrated increased peak vertical
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23 ground reaction forces (VGRF) and knee valgus and internal rotation angles at peak VGRF for
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25 the ipsilateral leg, but decreased peak VGRF and knee internal rotation angles at peak VGRF and
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27 increased knee varus angles at peak VGRF for the contralateral leg. Mid-flight lateral trunk
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29 resulted in an asymmetric landing pattern associated with increased ACL loading for the
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31 ipsilateral leg. The findings may help to understand altered trunk motion during ACL injury
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33 events and the discrepancy in ACL injuries related to limb dominance in badminton and
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35 volleyball.

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4 **41 Introduction**
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7 42 Athletes commonly suffer non-contact anterior cruciate ligament (ACL) injuries during jump-
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9 43 landing tasks (Devetag, Mazzilli, Benis, La Torre, & Bonato, 2016; Hewett, Torg, & Boden,
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11 44 2009; Kimura et al., 2010; Stuelcken, Mellifont, Gorman, & Sayers, 2016). Small knee flexion
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13 45 angles and increased knee abduction and internal rotation angles along with increased anterior
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15 46 tibial shear forces and tibiofemoral compressive forces are associated with increased ACL
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17 47 loading (Dai, Mao, Garrett, & Yu, 2014). Consistently, ACL injuries typically occur during the
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19 48 early phase of landing when individuals demonstrate small knee flexion angles, increased knee
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21 49 abduction and internal rotation angles, and altered trunk angles (Dai, Mao, Garrett, & Yu, 2015;
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24 50 Hewett et al., 2009; Koga et al., 2010; Krosshaug et al., 2007; Stuelcken et al., 2016). Therefore,
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26 51 jump-landing training with a goal to decrease ACL injury risk has been focused on decreasing
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28 52 impact ground reaction forces, increasing knee flexion, and minimizing non-sagittal plane knee
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30 53 motion (Dai, Garrett et al., 2015; Welling, Benjaminse, Gokeler, & Otten, 2016).

31 54 Compared to altered knee kinematics, the relationship between altered trunk motion and
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33 55 increased risk for ACL injury during jump-landing remains unclear. Increased lateral trunk
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35 56 bending to the side of injury has been observed in conjunction with increased knee abduction
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37 57 during ACL injuries in female basketball and netball players (Hewett et al., 2009; Stuelcken et
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39 58 al., 2016). When the foot is fixed on the ground, lateral trunk bending can result in an external
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41 59 hip abduction moment on the bending side, which needs to be balanced by an internal hip
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43 60 adduction moment. Such an internal hip adduction moment may cause the knee to move
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45 61 medially and increase external knee abduction moments during landing (Hewett & Myer, 2011).

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47 62 This mechanical connection between trunk and knee motion provides a plausible explanation for
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49 63 the increased lateral trunk bending observed during ACL injury events. A prospective study
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4 64 supports the connection between trunk control and ACL injury risk by showing that female
5 65 athletes with increased trunk displacements under sudden perturbation demonstrate increased
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7 66 risk for ACL injury (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007). Previous efforts
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9 67 to understand lateral trunk bending and ACL injury risk, however, have been focused on the
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11 68 landing phase (Hewett & Myer, 2011). Interestingly, badminton and volleyball, two sports that
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13 69 involve mid-flight trunk bending and reaching of the dominant arm, have shown increased ACL
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15 70 injury rates to the knee opposite to the dominant arm after landing (Devetag et al., 2016; Kimura
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17 71 et al., 2010). Quantifying how trunk motion prior to landing may affect landing biomechanics
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19 72 can provide additional information for understanding the relationship between lateral trunk
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21 73 bending and ACL injury risk.

22
23 74 Relatively few studies have quantified the effect of mid-flight trunk motion on landing
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25 75 mechanics (Dempsey, Elliott, Munro, Steele, & Lloyd, 2012; Yom, Simpson, Arnett, & Brown,
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27 76 2014). Dempsey et al. (2012) found that landing after catching a ball that was lateral to the
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29 77 landing leg increased peak knee valgus moments compared with landing after catching a ball
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31 78 medial to the landing leg. The participants in this study, however, were instructed to land with a
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33 79 single leg on a force platform. Single-leg landings result in changes in lower extremity
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35 80 biomechanics that are associated with greater ACL loading compared with double-leg landing
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37 81 (Donohue et al., 2015; Yeow, Lee, & Goh, 2010). Whether participants would unintentionally
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39 82 adopt a single-leg landing after mid-flight trunk motion remains unknown. Yom et al. (2014)
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41 83 demonstrated that landing after mid-flight trunk perturbation induced by an external pulling force
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43 84 resulted in increased peak ground reaction forces, increased knee abduction angles, and
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45 85 decreased knee flexion angles for the leg on the same side of the pulling force. A pulling force
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47 86 simulates ACL injuries that involve mid-flight contact with other players, and whether this

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4 87 contact contributes to the injury situation warrants future investigation. However, this method of
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6 88 trunk perturbation may not represent other ACL injury scenarios, during which individuals have
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8 89 no mid-flight contact with other players.
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11 90 Athletes commonly perform self-initiated mid-flight lateral trunk bending during sports
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13 competition (Kimura et al., 2010). Mid-flight lateral trunk bending may cause re-positioning of
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15 segmental centers of mass (COM) and affect landing mechanics. Newton's laws indicate that an
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17 individual's whole body COM in the air will demonstrate a parabola shaped trajectory when air
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19 resistance is negligible. Therefore, when specific body segments move in one direction relative
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21 to the whole body COM in mid-flight, some other segments must move in the opposite direction.
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25 96 The purpose of the current study was to quantify the effect of mid-flight lateral trunk
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27 bending on COM positions and subsequent landing mechanics during a jump-landing task. It was
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29 hypothesized that lateral trunk bending in one direction would cause leg movements in the
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31 opposite direction. Consequently, the ipsilateral leg would be displaced closer to the whole body
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33 COM, while the contralateral leg would be displaced further away from the whole body COM in
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35 the mediolateral direction. Based on the literature (Dempsey et al., 2012; Yom et al., 2014), it
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37 was also hypothesized that the ipsilateral leg would experience increased peak vertical ground
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39 reaction forces (VGRF), decreased knee flexion angles at peak VGRF, and increased knee valgus
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41 and internal rotation angles at peak VGRF when landing after mid-flight lateral trunk bending
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44 104 compared with landing without mid-flight lateral trunk bending.
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55 107 **Methods**
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4 109 Based on previous studies which quantified the effect of mid-flight trunk motion or perturbation
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6 110 on landing biomechanics (Dempsey et al., 2012; Yom et al., 2014), a medium to large effect size
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8 111 was expected for the current study. Assuming a medium effect size of 0.5 for a paired t-test, a
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10 112 sample size of 34 was needed for a type I error at the level of 0.05 to achieve a power of 0.8.
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13 113 Forty-one participants were recruited (sex: 18 males, 23 females; age: 22.0 ± 3.0 years; height:
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15 114 1.74 ± 0.10 m; mass: 71.0 ± 13.9 kg). All participants preferred to use the right arm to throw a
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17 football for further distance. Twenty-eight of them preferred to jump off the right leg for a
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19 115 further distance. Participants had experience with sports that involved jump-landing tasks and
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21 116 participated in sports or exercise at least two times for a total of two to three hours per week at
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23 117 the time of testing. Exclusion criteria were described in a previous study (Dai, Garrett et al.,
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25 118 2015). This study was approved by the University of Wyoming Institutional Review Board.
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30 120 Participants signed informed consent forms and completed a questionnaire to screen for
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32 121 exclusion criteria prior to data collection.

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36 123 *Procedures*
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39 124 Participants wore a baseball cap, spandex pants, a spandex shirt, and standard athletic shoes
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41 125 (Ghost 5, Brooks Sports Inc. Seattle, WA, USA). Participants completed a standard warm-up
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43 126 including five minutes of running at a self-selected speed on a treadmill and a dynamic stretching
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45 127 protocol. Retroreflective markers were placed on a participant's vertex, gonions, sternum,
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47 128 acromioclavicular joints, olecranon processes, mid-points of radial and ulnar styloid processes,
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49 129 third metacarpal heads, anterior superior iliac spines, posterior superior iliac spines, iliac crests,
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51 130 greater trochanters, lateral thighs, anterior thighs, medial and lateral femoral condyles, superior
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4 131 and inferior shanks, lateral shanks, medial and lateral malleolus, tips of big toes, heels, and the
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6 132 fifth metatarsal heads (Figure 1).
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16 136 After a static trial, participants performed a vertical counter-movement jump-landing task
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19 137 with or without lateral trunk bending. The jump-landing task was designed to simulate basketball
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21 138 rebounding and volleyball blocking, during which athletes laterally bend their trunk and reach
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24 139 both hands to catch or block a ball. This task also had implication for volleyball spiking and
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26 140 badminton smashing, both of which involved lateral trunk bending and one hand reaching.
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29 141 Participants started with feet shoulder-width apart and one foot on each of the two force
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31 142 platforms. In the Up condition, participants were instructed to jump for maximum height and
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33 143 reach both hands in the up direction without laterally bending their trunk (Figure 2). In the Right
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35 144 Bending or Left Bending condition, participants were instructed to jump for maximum height
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37 145 and bend their trunk to the right or left as far as they could and reach both hands to the right or
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39 146 left when they reach their maximum height (Figure 2). In all three conditions, participants were
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41 147 instructed to land with one foot on each of the two force platforms. A trial was repeated if
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43 148 participants did not land on targeted force platforms. No other instruction regarding body
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46 149 movements or landing techniques was given. Participants practiced each jump-landing task for a
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48 150 minimum of two trials, followed by three official trials. Participants were given a minimum of
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50 151 30-second rest between trials. The order of the three jump-landing tasks was randomized for
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52 152 each participant.
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Figure 1 near here

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**

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4 177 rotation between the thigh and shank reference frames. Knee joint angles during the static trials
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6 178 were defined as the neutral alignment and subtracted from the angles during jump-landing trials.
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11 180 Table 1 near here
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16 182 Takeoff was defined as the first time event when both feet were off the force platforms.
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19 183 Maximum Height was defined as the time event when the whole body COM reached maximum
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21 184 height. First Initial Landing was defined as the time event when the **first** foot landed on a force
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23 185 platform. Second Initial Landing was defined as the time event when the **second** foot landed on a
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25 186 force platform. The lateral trunk bending angles and COM of the upper body, pelvis, ipsilateral
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27 187 leg, and contralateral leg positions relative to the whole body COM in the mediolateral direction
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29 188 was calculated at Takeoff, Maximum Height, and First Initial Landing. For the Left Bending and
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31 189 Right Bending conditions, the direction of the bending side was defined as positive. For the Up
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33 190 condition, the right direction was defined as positive and the right leg was the ipsilateral leg.
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35 191 COM positions were normalized as a percentage of the participants' body height.
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38 192 Time differences between the First and Second Initial Landing were calculated with
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40 193 landing of the ipsilateral leg prior to the contralateral leg defined as positive. ACL injuries
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42 typically occur during the first 100 ms after initial contact (Dai et al., 2014). In addition,
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44 194 increased impact GRF, knee valgus and internal rotation angles as well as decreased knee flexion
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46 195 angles are associated with increased ACL loading (Dai et al., 2014). Therefore, the peak VGRF
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48 196 during the first 100 ms after initial landing was quantified for each leg. Knee flexion, valgus, and
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50 197 internal rotation angles at the peak VGRF were extracted for each leg. VGRF was normalized to
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52 198 the participants' body weight. Jump height was calculated relative to the whole body COM
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4 200 during static trials and jump-landing trials to quantify jump performance. Calculations were
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6 201 performed using customized subroutines developed in MATLAB 2016b (MathWorks Inc. Natick,
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14 204 *Statistical Analysis*
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16 205 Data for the three official trials for each jump-landing condition for each participant were
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18 206 averaged for analysis. COM positions, lower extremity kinematic and kinetic variables, and jump
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20 207 height were compared among the three jump-landing conditions using repeated measures
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22 analyses of variance (ANOVA). When an ANOVA showed a significant main effect, paired t-
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24 208 tests were performed between each pair of two jump-landing conditions. A type-I error rate was
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26 209 set at 0.05 for **the** ANOVAs for statistical significance. A procedure was applied to all paired t-
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28 210 tests to control the study-wide false discovery rate at 0.05 (Benjamini & Hochberg, 1995).
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30 211 Cohen's dz was calculated to evaluate the effect size of changes in jump height and landing
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32 212 variables between two jump-landing conditions with Cohen's dz ≥ 0.8 considered "large," $0.5 <$
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34 213 Cohen's dz < 0.8 considered "medium," and Cohen's dz < 0.5 considered "small" (Cohen, 1988).
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37 214 Statistical analyses were performed using SPSS Statistics 24 software (IBM Corporation,
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39 215 Armonk, NY, USA).
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48 218 **Results**
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51 219 ANOVAs showed significant main effects ($p < 0.05$) for all variables except for knee flexion
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53 220 angles at peak VGRF for both ipsilateral and contralateral legs. A total of 69 paired t-tests were
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55 221 performed for the other 23 variables, and the largest p value for a significant paired t-test was
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57 222 0.026 after the adjustment for the false discovery rate.
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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.

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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

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4 246 support the hypothesis that mid-flight lateral trunk bending in one direction would cause leg
5 movements in the opposite direction. Since participants jumped vertically, the mid-flight
6 trajectory of the whole body COM should be close to a straight line. Lateral trunk bending was
7 characterized by lateral movements of the upper body, which comprised of nearly 50% of total
8 body mass. Consequently, this resulted in opposite movements in the rest of the segments. As
9 shown in the ensemble curves, for the left and right trunk bending conditions, upper body COM
10 started to move in the bending direction at Takeoff, suggesting a preparatory strategy during the
11 jumping phase. This modification likely altered the jump strategy, as jump height was decreased
12 in the two lateral trunk bending conditions. Participants continued to move their upper body in
13 the bending direction and other segments in the opposite direction after Takeoff. As both legs
14 moved opposite to the bending direction, the ipsilateral leg moved medially toward the whole
15 body COM. Meanwhile, the contralateral leg moved laterally away from the whole body COM.
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18 258 The findings support the hypothesis that the ipsilateral leg would demonstrate greater
19 peak VGRF when landing after lateral trunk bending compared with landing without lateral
20 trunk bending. These findings are consistent with the studies by Dempsey et al. (2012) and Yom
21 et al. (2014), showing that lateral trunk bending increased ipsilateral leg loading. In the current
22 study, movement was induced by self-initiated lateral trunk bending compared to an external
23 force (Yom et al, 2014). Therefore, the current findings may be more relevant for ACL injuries
24 not involving mid-flight external contact. The current study also differed from Dempsey et al,
25 (2012) by observing asymmetric landing patterns when participants were allowed to land on two
26 legs, which may represent a different sports scenario. The ipsilateral leg tended to land earlier
27 and was closer to the whole body COM compared with the contralateral leg. These two factors
28 may contribute to the increased peak VGRF experienced by the ipsilateral leg for the lateral
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4 269 trunk bending conditions. The findings suggest that mid-flight lateral trunk bending, which is
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6 270 integral to many sports, can lead to asymmetric landing patterns.
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9 271 The findings also support the hypothesis that the ipsilateral leg would demonstrate
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11 272 increased knee valgus and knee internal rotation angles. However, they do not support the
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13 273 hypothesis that the ipsilateral leg would demonstrate decreased knee flexion angles after landing
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15 274 with lateral trunk bending. Lateral trunk bending persisted from Maximum Height to Landing.
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17 275 Increased lateral trunk bending at landing may contribute to the increased knee valgus angles at
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19 276 peak VGRF for the ipsilateral leg as previously described (Hewett & Myer, 2011). On the other
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21 277 hand, lateral trunk bending resulted in opposite changes to the contralateral leg and increased its
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23 278 knee varus angles at peak VGRF. **In addition, knee internal rotation angles also increased for the**
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25 279 **ipsilateral leg but decreased for the contralateral leg.** Previously studies have observed decreased
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27 280 knee flexion angles during single-leg landings compared with double-leg landings (Donohue et
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29 281 al., 2015; Yeow et al., 2010). In the current study, participants landed with each foot on a force
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31 282 platform. Although the ipsilateral leg landed earlier, the time differences on average were less
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33 283 than 20 ms with small effect sizes. Therefore, the changes in knee flexion angles were much less
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35 284 compared with solely landing on a single leg. **An** increased landing pattern asymmetry may
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37 285 produce changes in knee flexion angles more comparable to those seen in single-leg landings. In
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39 286 summary, the ipsilateral leg demonstrated increased impact GRF, knee abduction, and internal
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41 287 rotation angles at peak VGRF, which have been associated with increased ACL loading (Dai et
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43 288 al., 2014). These findings are consistent with a previous study, showing increased lateral trunk
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45 289 bending to the injured leg when ACL injuries occur (Hewett et al., 2009).

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47 290 The findings may also help explain the discrepancies in ACL injury rates related to limb
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49 291 dominance in certain sports. In volleyball and badminton, players use their dominant arms to
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4 292 spike a ball or smash a shuttlecock. In badminton, of the ACL injuries that occurred during
5 landing after an overhead stroke, 90% were to the knee opposite to the dominant arm (Kimura et
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7 293 al., 2010). In volleyball, of the injuries occurred during landing from a jump attack, 67% were to
8 the knee opposite to the dominant arm (Devetag et al., 2016). A ball or shuttlecock on a player's
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10 294 dominant-arm side can be reached by extending the dominant shoulder and elbow. One on the
11 non-dominant-arm side a similar distance away may require lateral trunk bending to the non-
12
13 295 dominant-arm side. The greater mass of a trunk compared with the mass of an arm may induce
14 greater perturbation to the body and increase landing asymmetries. In addition, lateral trunk
15 bending to the non-dominant-arm side will elevate the height of the dominant shoulder,
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17 296 potentially allowing players to contact the ball or shuttlecock at a higher point. In fact, of the
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19 297 ACL injuries occurred during landing after an overhead stroke in badminton, most occurred in a
20 court position that was opposite to the dominant arm (Kimura et al., 2010). When volleyball
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22 298 players (96% right-side dominant) landed on a single leg after a jump attack, the probabilities of
23 landing on the left were much greater than landing on the right leg (Lobietti, Coleman,
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25 299 Pizzichillo, & Merni, 2010). In addition, spiking a ball set to the left side of the front court
26 resulted in a much higher percentage of single-leg landings compared with spiking a ball set to
27 the right side of the frontal court (Lobietti et al., 2010). In summary, badminton and volleyball
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29 players are more likely to bend their trunk to the non-dominant-arm side, which may increase the
30 loading to the knee opposite to the dominant arm and contribute to its increased ACL injury rates.
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33 311 Multiple strategies may be used to decrease the loading imposed to the ipsilateral leg
34 associated with mid-flight lateral trunk bending. First, after completing a sports task which
35 involves lateral trunk bending in mid-flight, individuals can try to return their trunk to an upright
36 position, so that two legs can land at similar times and experience balanced loading.
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4 315 Proprioception and core strength (Zazulak et al., 2007), common targets of ACL injury
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6 316 prevention programs (Brown, Palmieri-Smith, & McLean, 2014), may be important factors in the
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8 317 application of this strategy. Second, individuals may increase knee and hip flexion in the air to
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10 318 have more time to adjust their trunk position and prepare for a soft landing (Dai, Garrett et al.,
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12 319 2015). Third, if there is excessive lateral trunk bending and the contralateral leg is not close to
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14 320 the whole body COM, softly landing on the ipsilateral leg, while transitioning to a safe **fall to the**
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16 321 **trunk bending direction**, may be a good option. Utilization of these strategies will depend on an
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18 322 individual's physical capacity and performance goals as well as the demands of each specific
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20 323 sports situation. Previous jump-landing training has been focused on minimizing landing errors
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22 324 (Mandelbaum et al., 2005; Padua et al., 2012). It may also be beneficial to screen and train
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24 325 landing patterns with mid-flight lateral trunk bending.
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31 326 Several limitations existed in the current study. First, since the lateral trunk bending was
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33 327 anticipated, it may not be representative of scenarios characterized by mid-flight reactions to
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35 328 dynamic environments. Future studies are needed to incorporate actual objects for reaching, shift
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37 329 of attention, and decision making to better simulate a real sports scenario. Second, the exact
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39 330 amount of lateral trunk bending was quantified but not controlled. Instead, participants laterally
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41 331 bent their trunk as far as possible while still landing with each foot on a force platform. More
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43 332 extreme lateral trunk bending may occur if foot placements were not constrained, but this may
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45 333 also raise safety concerns. Finally, the current findings do not account for differences that might
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47 334 exist among athletes from various sports. All participants were right-handed and tended to
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49 335 demonstrate greater lateral trunk bending to the left than to the right. This increased trunk
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51 336 bending toward the non-dominant arm might be related to previous experience.
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4 338 **Conclusions**
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7 339 Mid-flight lateral trunk bending caused movements of the pelvis and two legs in the opposite
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9 340 direction of the bending side and resulted in an asymmetric landing posture. The lateral trunk
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11 341 bending and asymmetric posture resulted in landing biomechanics associated with increased
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14 342 ACL loading for the ipsilateral leg. The current findings may **provide** additional information for
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16 343 understanding the role of altered trunk motion observed during ACL injury events and the
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19 344 discrepancy in ACL injury rates related to limb dominance in badminton and volleyball.
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4 439 Figure Captions
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6 440 Figure 1. Frontal and side views of marker placement
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8 441 Figure 2. Up (top) and Right Bending (bottom) conditions at different time events for the jump-
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10 442 landing task
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12 443 Figure 3. Ensemble curves with the 95% confidence interval of the mean for lateral trunk
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14 444 bending angles from Takeoff to Landing for the Left Bending, Right Bending, and Up conditions.
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16 445 Figure 4. Ensemble curves with the 95% confidence interval of the mean for upper body center
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18 446 of mass (COM) positions relative to whole body COM from Takeoff to Landing for the Left
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20 447 Bending, Right Bending, and Up conditions.
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23 448 Figure 5. Ensemble curves with the 95% confidence interval of the mean for pelvis center of
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25 449 mass (COM) positions relative to whole body COM from Takeoff to Landing for the Left
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27 450 Bending, Right Bending, and Up conditions.
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30 451 Figure 6. Ensemble curves with the 95% confidence interval of the mean for ipsilateral leg center
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32 452 of mass (COM) positions relative to whole body COM from Takeoff to Landing for the Left
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36 454 Figure 7. Ensemble curves with the 95% confidence interval of the mean for contralateral leg
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38 455 center of mass (COM) positions relative to whole body COM from Takeoff to Landing for Left
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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
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 30% distal, 14% medial, and 22% posterior of the distance between the two anterior superior iliac spines to the anterior superior iliac spine		Third Metacarpal	Third metacarpal head		0.56	0.61	74.74	79.00	
Thigh	Hip Center			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	

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

5 **ABSTRACT**

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

21

22 **Introduction**

23 Athletes commonly suffer non-contact anterior cruciate ligament (ACL) injuries during jump-
24 landing tasks (Devetag, Mazzilli, Benis, La Torre, & Bonato, 2016; Hewett, Torg, & Boden,
25 2009; Kimura et al., 2010; Stuelcken, Mellifont, Gorman, & Sayers, 2016). Small knee flexion
26 angles and increased knee abduction and internal rotation angles along with increased anterior
27 tibial shear forces and tibiofemoral compressive forces are associated with increased ACL
28 loading (Dai, Mao, Garrett, & Yu, 2014). Consistently, ACL injuries typically occur during the
29 early phase of landing when individuals demonstrate small knee flexion angles, increased knee
30 abduction and internal rotation angles, and altered trunk angles (Dai, Mao, Garrett, & Yu, 2015;
31 Hewett et al., 2009; Koga et al., 2010; Krosshaug et al., 2007; Stuelcken et al., 2016). Therefore,
32 jump-landing training with a goal to decrease ACL injury risk has been focused on decreasing
33 impact ground reaction forces, increasing knee flexion, and minimizing non-sagittal plane knee
34 motion (Dai, Garrett et al., 2015; Welling, Benjaminse, Gokeler, & Otten, 2016).

35 Compared to altered knee kinematics, the relationship between altered trunk motion and
36 increased risk for ACL injury during jump-landing remains unclear. Increased lateral trunk
37 bending to the side of injury has been observed in conjunction with increased knee abduction
38 during ACL injuries in female basketball and netball players (Hewett et al., 2009; Stuelcken et
39 al., 2016). When the foot is fixed on the ground, lateral trunk bending can result in an external
40 hip abduction moment on the bending side, which needs to be balanced by an internal hip
41 adduction moment. Such an internal hip adduction moment may cause the knee to move
42 medially and increase external knee abduction moments during landing (Hewett & Myer, 2011).
43 This mechanical connection between trunk and knee motion provides a plausible explanation for
44 the increased lateral trunk bending observed during ACL injury events. A prospective study

45 supports the connection between trunk control and ACL injury risk by showing that female
46 athletes with increased trunk displacements under sudden perturbation demonstrate increased
47 risk for ACL injury (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007). Previous efforts
48 to understand lateral trunk bending and ACL injury risk, however, have been focused on the
49 landing phase (Hewett & Myer, 2011). Interestingly, badminton and volleyball, two sports that
50 involve mid-flight trunk bending and reaching of the dominant arm, have shown increased ACL
51 injury rates to the knee opposite to the dominant arm after landing (Devetag et al., 2016; Kimura
52 et al., 2010). Quantifying how trunk motion prior to landing may affect landing biomechanics
53 can provide additional information for understanding the relationship between lateral trunk
54 bending and ACL injury risk.

55 Relatively few studies have quantified the effect of mid-flight trunk motion on landing
56 mechanics (Dempsey, Elliott, Munro, Steele, & Lloyd, 2012; Yom, Simpson, Arnett, & Brown,
57 2014). Dempsey et al. (2012) found that landing after catching a ball that was lateral to the
58 landing leg increased peak knee valgus moments compared with landing after catching a ball
59 medial to the landing leg. The participants in this study, however, were instructed to land with a
60 single leg on a force platform. Single-leg landings result in changes in lower extremity
61 biomechanics that are associated with greater ACL loading compared with double-leg landing
62 (Donohue et al., 2015; Yeow, Lee, & Goh, 2010). Whether participants would unintentionally
63 adopt a single-leg landing after mid-flight trunk motion remains unknown. Yom et al. (2014)
64 demonstrated that landing after mid-flight **trunk** perturbation induced by an external pulling force
65 resulted in increased peak ground reaction forces, increased knee abduction angles, and
66 decreased knee flexion angles for the leg on the same side of the pulling force. A **pulling force**
67 **simulates ACL injuries that involve mid-flight contact with other players, and whether this**

68 contact contributes to the injury situation warrants future investigation. However, this method of
69 trunk perturbation may not represent other ACL injury scenarios, during which individuals have
70 no mid-flight contact with other players.

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

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

87

88 **Methods**

89 *Participants*

90 Based on previous studies which quantified the effect of mid-flight trunk motion or perturbation
91 on landing biomechanics (Dempsey et al., 2012; Yom et al., 2014), a medium to large effect size
92 was expected for the current study. Assuming a medium effect size of 0.5 for a paired t-test, a
93 sample size of 34 was needed for a type I error at the level of 0.05 to achieve a power of 0.8.
94 Forty-one participants were recruited (sex: 18 males, 23 females; age: 22.0 ± 3.0 years; height:
95 1.74 ± 0.10 m; mass: 71.0 ± 13.9 kg). All participants preferred to use the right arm to throw a
96 football for further distance. Twenty-eight of them preferred to jump off the right leg for a
97 further distance. Participants had experience with sports that involved jump-landing tasks and
98 participated in sports or exercise at least two times for a total of two to three hours per week at
99 the time of testing. Exclusion criteria were described in a previous study (Dai, Garrett et al.,
100 2015). This study was approved by XXX Institutional Review Board. Participants signed
101 informed consent forms and completed a questionnaire to screen for exclusion criteria prior to
102 data collection.

103

104 *Procedures*

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

112 and inferior shanks, lateral shanks, medial and lateral malleolus, tips of big toes, heels, and the
113 fifth metatarsal heads (Figure 1).

114

115 Figure 1 near here

116

117 After a static trial, participants performed a vertical counter-movement jump-landing task
118 with or without lateral trunk bending. The jump-landing task was designed to simulate basketball
119 rebounding and volleyball blocking, during which athletes laterally bend their trunk and reach
120 both hands to catch or block a ball. This task also had implication for volleyball spiking and
121 badminton smashing, both of which involved lateral trunk bending and one hand reaching.

122 Participants started with feet shoulder-width apart and one foot on each of the two force
123 platforms. In the Up condition, participants were instructed to jump for maximum height and
124 reach both hands in the up direction without laterally bending their trunk (Figure 2). In the Right
125 Bending or Left Bending condition, participants were instructed to jump for maximum height
126 and bend their trunk to the right or left as far as they could and reach both hands to the right or
127 left when they reach their maximum height (Figure 2). In all three conditions, participants were
128 instructed to land with one foot on each of the two force platforms. A trial was repeated if
129 participants did not land on targeted force platforms. No other instruction regarding body
130 movements or landing techniques was given. Participants practiced each jump-landing task for a
131 minimum of two trials, followed by three official trials. Participants were given a minimum of
132 30-second rest between trials. The order of the three jump-landing tasks was randomized for
133 each participant.

134

135

Figure 2 near here

136

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

143

144 *Data Reduction*

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

158 rotation between the thigh and shank reference frames. Knee joint angles during the static trials
159 were defined as the neutral alignment and subtracted from the angles during jump-landing trials.

160

161 Table 1 near here

162

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

173 Time differences between the First and Second Initial Landing were calculated with
174 landing of the ipsilateral leg prior to the contralateral leg defined as positive. ACL injuries
175 typically occur during the first 100 ms after initial contact (Dai et al., 2014). In addition,
176 increased impact GRF, knee valgus and internal rotation angles as well as decreased knee flexion
177 angles are associated with increased ACL loading (Dai et al., 2014). Therefore, the peak VGRF
178 during the first 100 ms after initial landing was quantified for each leg. Knee flexion, valgus, and
179 internal rotation angles at the peak VGRF were extracted for each leg. VGRF was normalized to
180 the participants' body weight. Jump height was calculated relative to the whole body COM

181 during static trials and jump-landing trials to quantify jump performance. Calculations were
182 performed using customized subroutines developed in MATLAB 2016b (MathWorks Inc. Natick,
183 MA).

184

185 *Statistical Analysis*

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

198

199 **Results**

200 ANOVAs showed significant main effects ($p < 0.05$) for all variables except for knee flexion
201 angles at peak VGRF for both ipsilateral and contralateral legs. A total of 69 paired t-tests were
202 performed for the other 23 variables, and the largest p value for a significant paired t-test was
203 0.026 after the adjustment for the false discovery rate.

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

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

220

221 Tables 2-3 near here

222 Figures 3-7 near here

223

224 Discussion

225 The purpose of the current study was to quantify the effect of mid-flight lateral trunk bending on
226 COM positions and subsequent landing mechanics during a jump-landing task. The findings

227 support the hypothesis that mid-flight lateral trunk bending in one direction would cause leg
228 movements in the opposite direction. Since participants jumped vertically, the mid-flight
229 trajectory of the whole body COM should be close to a straight line. Lateral trunk bending was
230 characterized by lateral movements of the upper body, which comprised of nearly 50% of total
231 body mass. Consequently, this resulted in opposite movements in the rest of the segments. As
232 shown in the ensemble curves, for the left and right trunk bending conditions, upper body COM
233 started to move in the bending direction at Takeoff, suggesting a preparatory strategy during the
234 jumping phase. This modification likely altered the jump strategy, as jump height was decreased
235 in the two lateral trunk bending conditions. Participants continued to move their upper body in
236 the bending direction and other segments in the opposite direction after Takeoff. As both legs
237 moved opposite to the bending direction, the ipsilateral leg moved medially toward the whole
238 body COM. Meanwhile, the contralateral leg moved laterally away from the whole body COM.

239 The findings support the hypothesis that the ipsilateral leg would demonstrate greater
240 peak VGRF when landing after lateral trunk bending compared with landing without lateral
241 trunk bending. These findings are consistent with the studies by Dempsey et al. (2012) and Yom
242 et al. (2014), showing that lateral trunk bending increased ipsilateral leg loading. In the current
243 study, movement was induced by self-initiated lateral trunk bending compared to an external
244 force (Yom et al, 2014). Therefore, the current findings may be more relevant for ACL injuries
245 not involving mid-flight external contact. The current study also differed from Dempsey et al,
246 (2012) by observing asymmetric landing patterns when participants were allowed to land on two
247 legs, which may represent a different sports scenario. The ipsilateral leg tended to land earlier
248 and was closer to the whole body COM compared with the contralateral leg. These two factors
249 may contribute to the increased peak VGRF experienced by the ipsilateral leg for the lateral

250 trunk bending conditions. The findings suggest that mid-flight lateral trunk bending, which is
251 integral to many sports, can lead to asymmetric landing patterns.

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

271 The findings may also help explain the discrepancies in ACL injury rates related to limb
272 dominance in certain sports. In volleyball and badminton, players use their dominant arms to

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

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

296 Proprioception and core strength (Zazulak et al., 2007), common targets of ACL injury
297 prevention programs (Brown, Palmieri-Smith, & McLean, 2014), may be important factors in the
298 application of this strategy. Second, individuals may increase knee and hip flexion in the air to
299 have more time to adjust their trunk position and prepare for a soft landing (Dai, Garrett et al.,
300 2015). Third, if there is excessive lateral trunk bending and the contralateral leg is not close to
301 the whole body COM, softly landing on the ipsilateral leg, while transitioning to a safe **fall to the**
302 **trunk bending direction**, may be a good option. Utilization of these strategies will depend on an
303 individual's physical capacity and performance goals as well as the demands of each specific
304 sports situation. Previous jump-landing training has been focused on minimizing landing errors
305 (Mandelbaum et al., 2005; Padua et al., 2012). It may also be beneficial to screen and train
306 landing patterns with mid-flight lateral trunk bending.

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

318

319 **Conclusions**

320 Mid-flight lateral trunk bending caused movements of the pelvis and two legs in the opposite
321 direction of the bending side and resulted in an asymmetric landing posture. The lateral trunk
322 bending and asymmetric posture resulted in landing biomechanics associated with increased
323 ACL loading for the ipsilateral leg. The current findings may provide additional information for
324 understanding the role of altered trunk motion observed during ACL injury events and the
325 discrepancy in ACL injury rates related to limb dominance in badminton and volleyball.

326 Screening and training landing patterns following mid-flight lateral trunk bending is
327 recommended for ACL injury prevention programs.

328

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420 Figure Captions
421 Figure 1. Frontal and side views of marker placement
422 Figure 2. Up (top) and Right Bending (bottom) conditions at different time events for the jump-
423 landing task
424 Figure 3. Ensemble curves with the 95% confidence interval of the mean for lateral trunk
425 bending angles from Takeoff to Landing for the Left Bending, Right Bending, and Up conditions.
426 Figure 4. Ensemble curves with the 95% confidence interval of the mean for upper body center
427 of mass (COM) positions relative to whole body COM from Takeoff to Landing for the Left
428 Bending, Right Bending, and Up conditions.
429 Figure 5. Ensemble curves with the 95% confidence interval of the mean for pelvis center of
430 mass (COM) positions relative to whole body COM from Takeoff to Landing for the Left
431 Bending, Right Bending, and Up conditions.
432 Figure 6. Ensemble curves with the 95% confidence interval of the mean for ipsilateral leg center
433 of mass (COM) positions relative to whole body COM from Takeoff to Landing for the Left
434 Bending, Right Bending, and Up conditions.
435 Figure 7. Ensemble curves with the 95% confidence interval of the mean for contralateral leg
436 center of mass (COM) positions relative to whole body COM from Takeoff to Landing for Left
437 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
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 30% distal, 14% medial, and 22% posterior of the distance between the two anterior superior iliac spines to the anterior superior iliac spine		Third Metacarpal	Third metacarpal head		0.56	0.61	74.74	79.00	
Thigh	Hip Center			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
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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

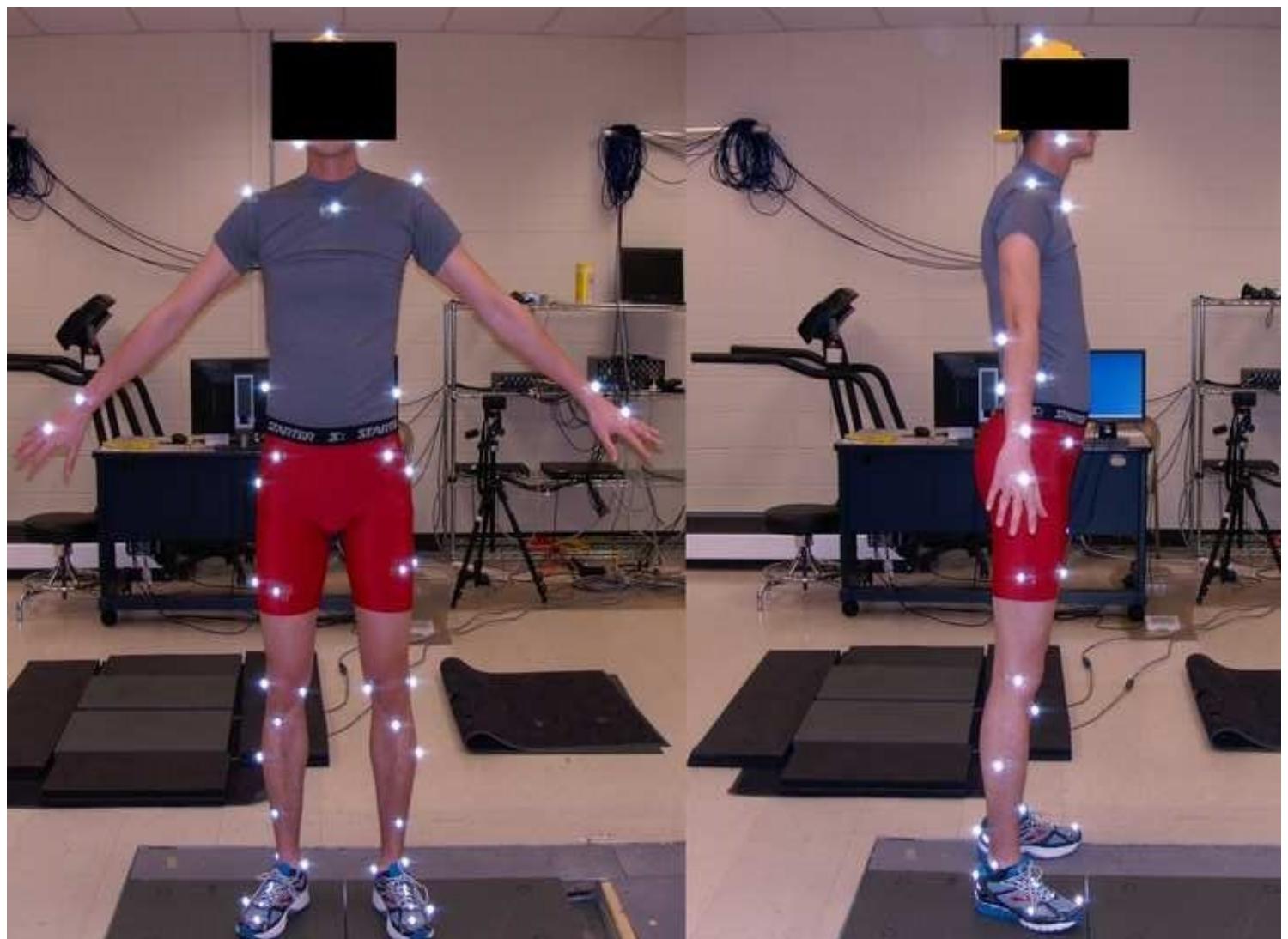


Figure 2

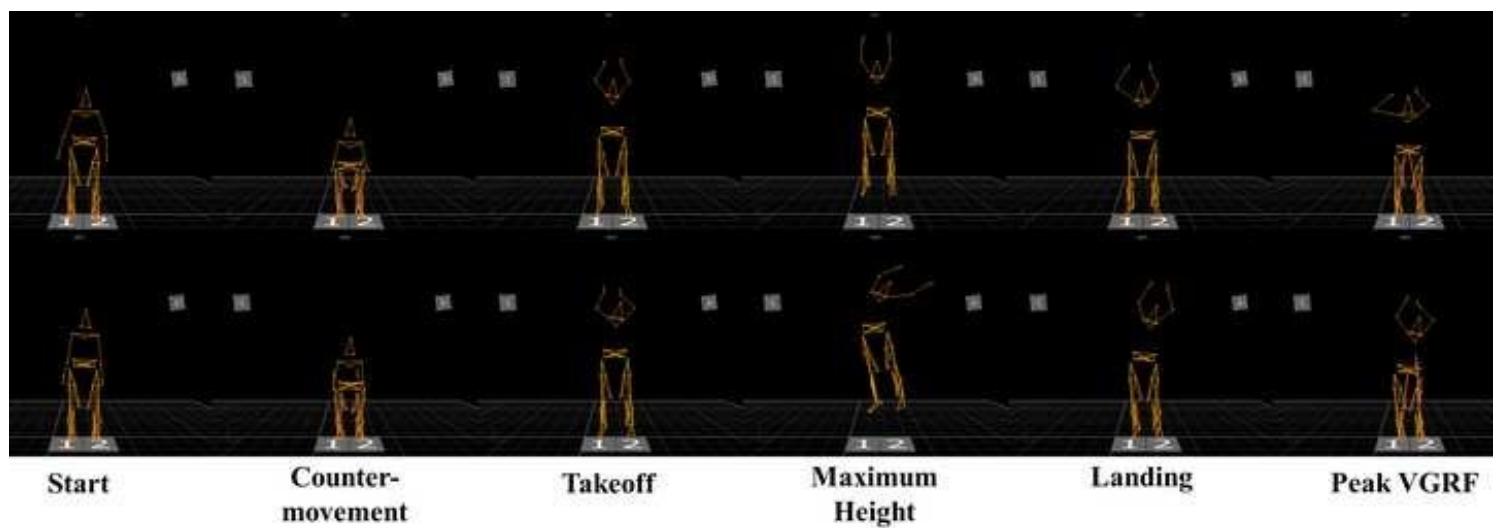


Figure 3

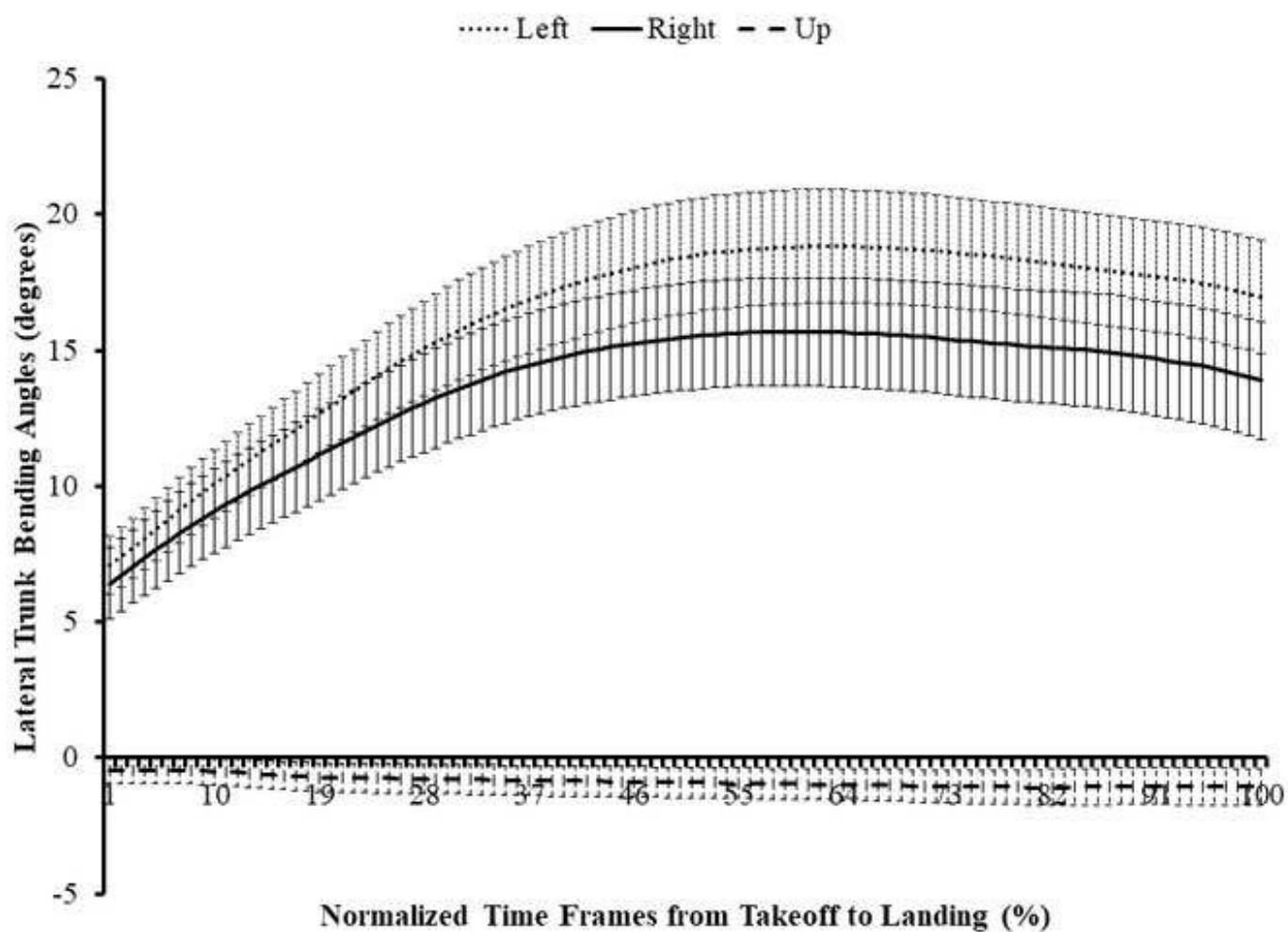


Figure 4

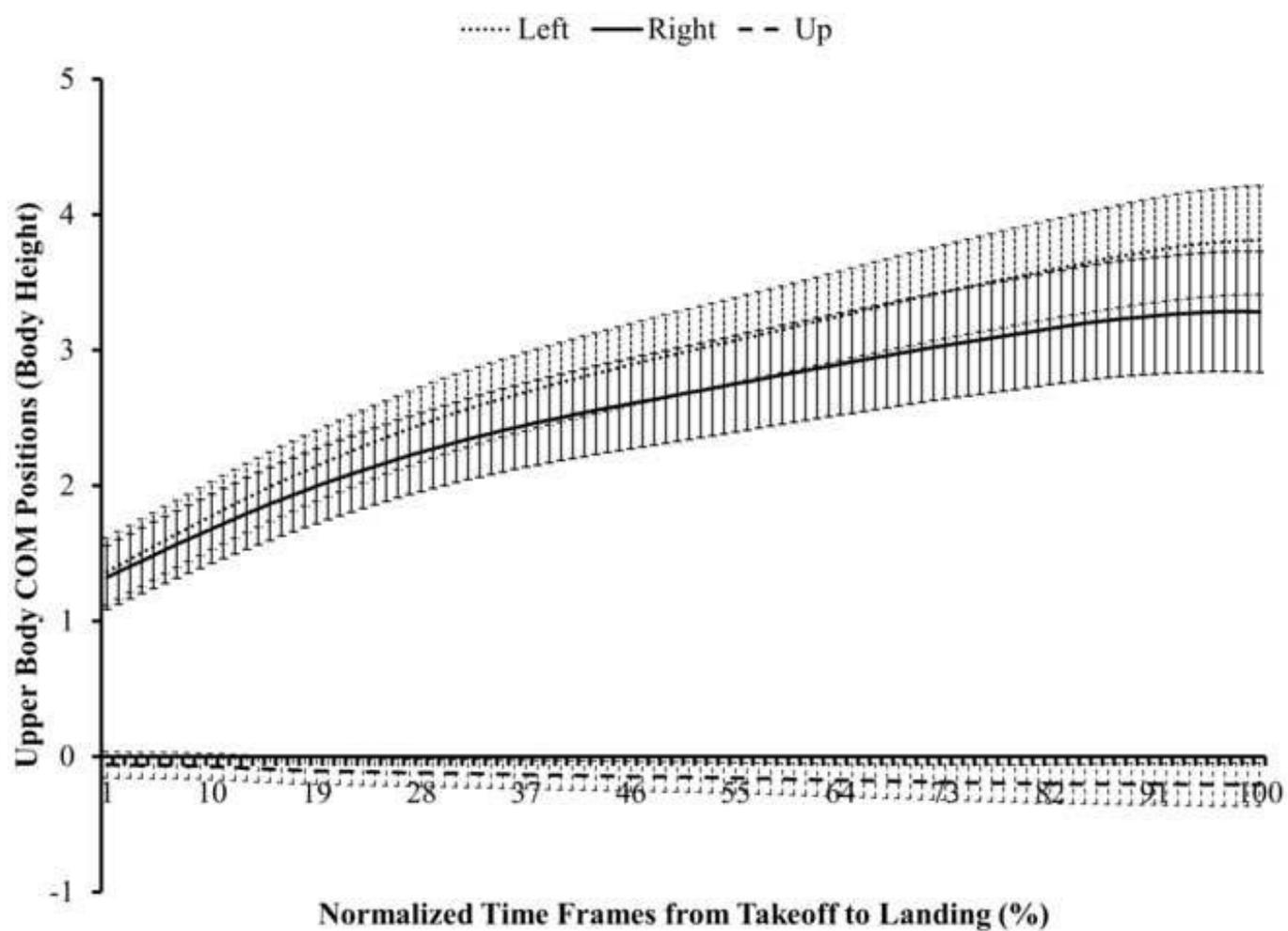


Figure 5

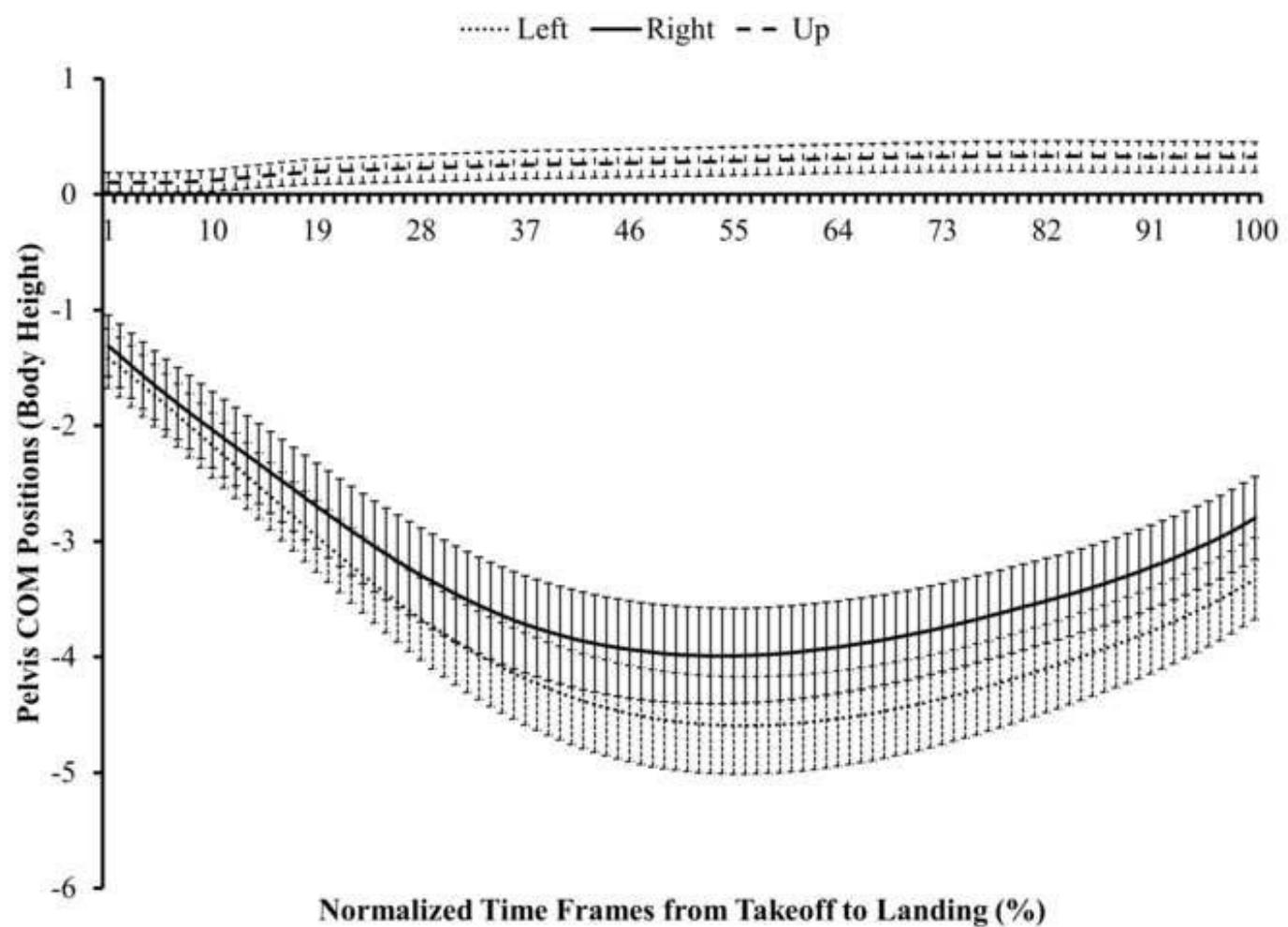


Figure 6

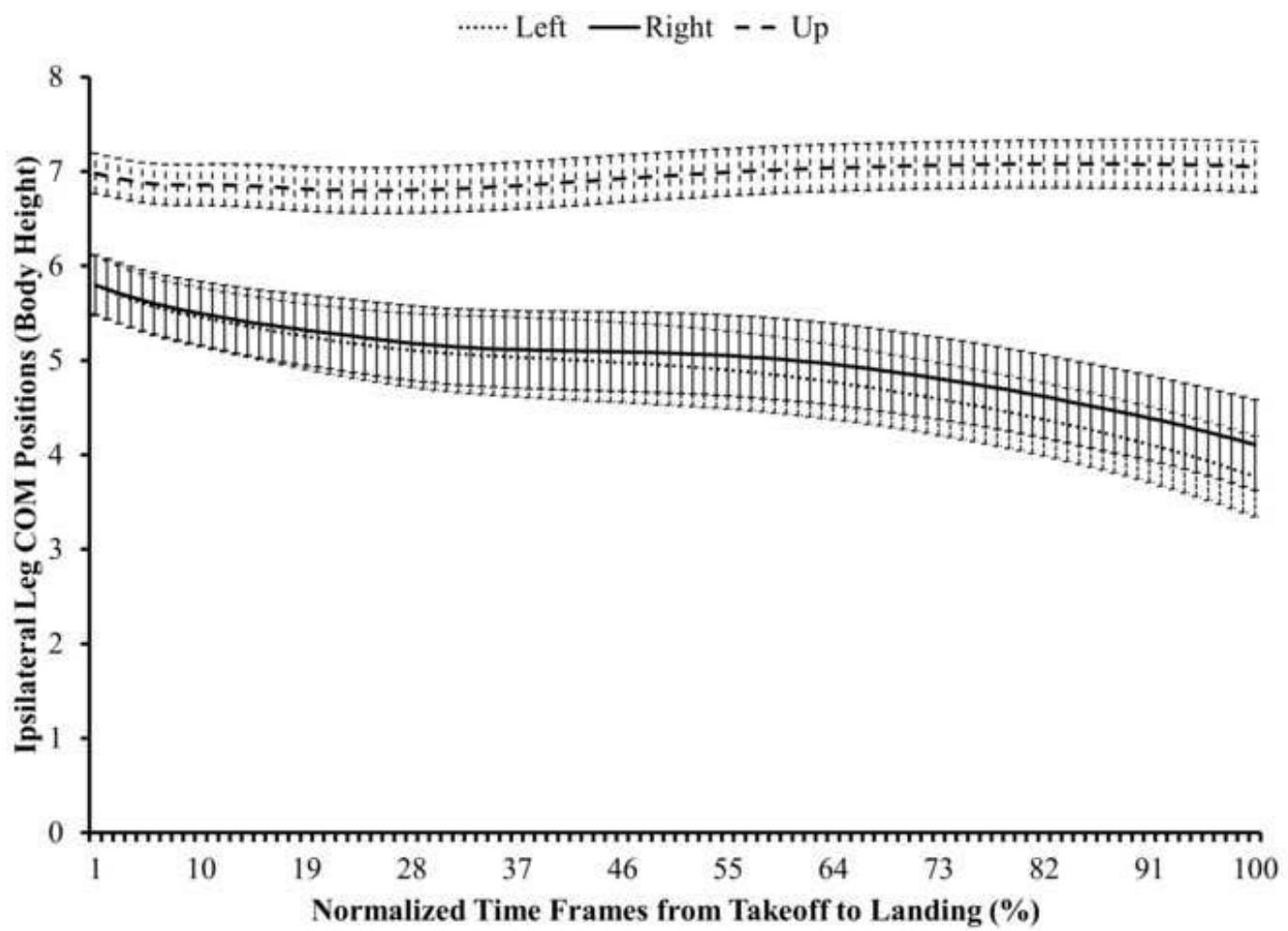


Figure 7

