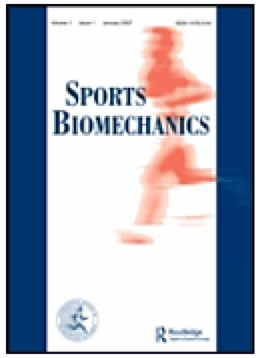

The Effects of Mid-flight Whole-Body and Trunk Rotation on Landing Mechanics: Implications for Anterior Cruciate Ligament Injuries

Journal:	*Sports Biomechanics*
Manuscript ID	RSPB-2018-0331.R2
Manuscript Type:	Original Research
Date Submitted by the Author:	04-Mar-2019

Complete List of Authors:	Critchley, Meghan; University of Wyoming Davis, Daniel; University of Wyoming Keener , Michaela; University of Wyoming Layer, Jacob; University of Wyoming Wilson, Margaret; University of Wyoming, Theatre & Dance Zhu, Qin; University of Wyoming, Division of Kinesiology and Health Dai, Boyi; University of Wyoming, Kinesiology and Health

Keywords:	Knee < Body, Injury < Sport Topics, Kinematics < Movement, Kinetics < Movement, ACL

Routledge
Taylor & Francis Group

Sports Biomechanics - Submission checklist

For resubmission

		Yes	No
1.	Have you prepared your point-by-point response to the Editor-in-Chief, Associate Editor, and each reviewer's comments? Do not group the responses. Place this document as the first document preceding the manuscript.	☑	☐
2.	Have you provided a clean version of the revision with the changes highlighted by coloured text or highlighter? Do not use track changes function as it makes the manuscript messy.	☑	☐

For new submission and resubmission

		Yes	No
1.	Is the quality of English sufficient for the peer review process? If not, please use a professional English editing service	☑	☐
2.	Have you prepared your manuscript with 'reader friendly' and 'coach friendly' plain language English?	☑	☐
3.	Have you avoided the overuse and the use of non-standard acronyms and abbreviations?	☑	☐
4.	Have you used British English spelling? (e.g. analyse, hypothesise, normalise)	☑	☐
5.	Have you used 'single quotation marks' instead of "double quotation marks"?	☑	☐
6.	Have you added continuous line numbers from abstract to appendices?	☑	☐
7.	Have you placed your documents in the following order: submission checklist, response to reviewer's comments (resubmission only), title page, abstract, keywords, main text, acknowledgements, references, appendices, table(s) with caption(s), figure captions on individual pages, and figure(s) as separated image files?	☑	☐
8.	Is the abstract in a single paragraph and within 200 words?	☑	☐
9.	Have you provided 3-5 keywords which are not included in the title?	☑	☐
10.	Is the rationale for the research clearly outlined in the introduction? i.e. have you made a compelling case for the relevance of the research undertaken?	☑	☐
11.	Have you used the following sections in the manuscript: Abstract, Introduction, Methods, Results, Discussion and Implications, Conclusion, References?	☑	☐
12.	Is there a clear research question stated and have testable hypotheses been included at the end of the introduction?	☑	☐
13.	Have you answered the testable hypotheses in 'Discussion and Implications' and/or Conclusion'?	☑	☐

14.	Have you used 'participants' instead of 'subjects' to refer to the human participants in the study?	☑	☐
15.	Have you used the required referencing format? A direct link is available here: http://www.tandf.co.uk/journals/authors/style/reference/tf_APA.pdf	☑	☐
16.	Have you checked the preferred units, symbols and numbers? (e.g. SI unit preferred, m/s but not ms^{-1}, avoid too many significant figures beyond the accuracy of your tool, use the same significant figures for mean and standard deviation, etc)	☑	☐
17.	Have you provided the figures in the highest quality, and placed them as separated files in the image format (i.e. JPG, TIFF)?	☑	☐
18.	Are there no more than 8 figures?	☑	☐
19.	Have you prepared a letter of submission including statements such as: • The manuscript is our own work. • The manuscript has not been published, and is not under consideration for publication elsewhere. It will not be submitted elsewhere for publication before your final editorial decision. • The manuscript contains nothing that is abusive, defamatory, libellous, obscene, fraudulent, or illegal. • We have no financial interest in the research reported in the manuscript.	☑	☐

Reviewer: 1

Comments to the Author

INTRODUCTION

Lines 113-117: There is still a disconnect between the literature cited and the authors' hypothesis. They cite a study that investigated lateral jumps without whole body rotation to support their hypothesis that "the leg contralateral to whole-body rotation […] would demonstrate less knee flexion angles and greater landing forces, knee moments, and knee abduction and internal rotation angled compared to …". Please revise.

Response: More information and clarification have been added to justify the use of the previous study to establish the current hypothesis. Line 102-105, 114-116

METHOD

Lines 203-205: This is merely a comment/remark with no change requested. I disagree that if the Benjamini & Hochberg procedure would be applied to the numerous repeated measures ANOVAs that were performed that the p-values for the multiple t-tests for each ANOVA would also have to be adjusted. As I mentioned in my original comment, it is my understanding that it is justifiable to perform those various t-tests to determine where the difference(s) lies, as indicated by the significant ANOVAs, without the need for additional adjustments for multiple comparisons.

Response: Thanks for reviewer's feedback without requesting changes. We believe both methods (ANOVAs and t-tests) are justifiable.

Reviewer: 2

Comments to the Author

Thanks to the authors for their detailed replies to my comments. I have no further comments.

Response: Thanks for reviewer's suggestions.

The Effects of Mid-flight Whole-Body and Trunk Rotation on Landing Mechanics: Implications for Anterior Cruciate Ligament Injuries

Meghan L. Critchley [1], Daniel J. Davis [1], Michaela M. Keener [1], Jacob S. Layer [1], Margaret A. Wilson [2], Qin Zhu [1], and Boyi Dai [1]

1. Division of Kinesiology and Health, University of Wyoming, Laramie, WY, USA

2. Department of Theatre and Dance, University of Wyoming, Laramie, WY, USA

Corresponding Author:

Boyi Dai, PhD

Division of Kinesiology and Health, University of Wyoming, Laramie, WY USA 82071

Phone: 1-3077665423; Fax: 1-3077664098; Email: bdai@uwyo.edu

Conflict of interest statement

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

Word Count (Introduction through Conclusion): 4285

Abstracts

The purpose was to quantify the effects of mid-flight whole-body and trunk rotation on knee mechanics in a double-leg landing. Eighteen male and twenty female participants completed a jump-landing-jump task in five conditions: no rotation, testing leg ipsilateral or contralateral (WBRC) to the whole-body rotation direction, and testing leg ipsilateral (TRI) or contralateral to the trunk rotation direction. The WBRC and TRI conditions demonstrated decreased knee flexion and increased knee abduction angles at initial contact (2.6 > Cohen's dz > 0.3) and increased peak vertical ground reaction forces and knee adduction moments during the 100 ms after landing (1.7 > Cohen's dz > 0.3). The TRI condition also showed the greatest knee internal rotation angles at initial contact and peak knee abduction and internal rotation angles and peak knee extension moments during the 100 ms after landing (2.0 > Cohen's dz > 0.5). Whole-body rotation increased contralateral knee loading because of its primary role in decelerating medial-lateral velocities. Trunk rotation resulted in the greatest knee loading for the ipsilateral knee due to weight shifting and mechanical coupling between the trunk and lower extremities. These findings may help understand altered trunk motion in anterior cruciate ligament injuries and develop training strategies.

Keywords: ACL; Knee; Injury; Kinematics; Kinetics;

Introduction

Anterior cruciate ligament (ACL) injuries are common severe injuries in athletes (Kay et al., 2017). While females demonstrated increased incidence rates of ACL injuries compared to males in several sport events (Kay et al., 2017), males suffered the majority of ACL injuries in the general population (Gianotti, Marshall, Hume, & Bunt, 2009; Granan, Bahr, Steindal, Furnes, & Engebretsen, 2008). Following ACL injuries, individuals demonstrate abnormal neuromuscular function, elevated risk for secondary injuries, and increased risk of knee osteoarthritis (Ingersoll, Grindstaff, Pietrosimone, & Hart, 2008; Kamath et al., 2014; Luc, Gribble, & Pietrosimone, 2014). ACL injuries frequently occur during jump-landing, cutting, and pivoting tasks and are characterised by small knee flexion, increased knee abduction, and increased knee internal/external rotation (Dai, Mao, Garrett, & Yu, 2015; Koga et al., 2010; Krosshaug et al., 2007; Olsen, Myklebust, Engebretsen, & Bahr, 2004). These injury characteristics are generally consistent with ACL loading mechanisms (Dai, Mao, Garrett, & Yu, 2014), although knee external rotation may decrease ACL loading (Utturkar et al., 2013). Consequently, jump-landing training has been focusing on soft landing with increased knee flexion and minimised knee abduction and rotation (Dai et al., 2015; DiStefano, Padua, DiStefano, & Marshall, 2009; Welling, Benjaminse, Gokeler, & Otten, 2016).

Compared to knee kinematics and kinetics, the biomechanical association between trunk motion and ACL loading is less clear. A more upright trunk and a more posteriorly positioned centre of mass were observed when basketball players sustained ACL injuries (Sheehan, Sipprell, & Boden, 2012). This position was likely to load the ACL due to the increased quadriceps forces required to prevent falling backward (Sheehan et al., 2012). Similarly, female basketball players demonstrated a more upright trunk and tended to exhibit increased lateral trunk bending and knee abduction to the injured leg in ACL injury events (Hewett, Torg, & Boden, 2009). Lateral trunk bending is likely increasing internal hip adduction moments, potentially moving the knee medially, and therefore increasing external knee abduction moments (Hewett & Myer, 2011). Two general scenarios were identified when female netball players sustained ACL injuries (Stuelcken, Mellifont, Gorman, & Sayers, 2016). In the first, players experienced a mid-flight perturbation followed by an unbalanced landing. The second scenario consisted of lateral trunk bending toward the injured side with trunk rotation away from the injured leg. The trunk was also more likely to rotate away from the injured leg when male soccer players experienced ACL injuries (Walden et al., 2015). These studies suggest altered trunk motion may play a role in ACL injury events and support the correlation between poor trunk control and ACL injury risk (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007). However, most previous studies have analysed trunk motion in ACL events using two-dimensional videos captured from uncalibrated cameras, which may introduce significant errors (Dai et al., 2015; Koga et al., 2010). Further validation of the relationship between trunk motion and factors associated with ACL loading is warranted.

Several studies have quantified the effect of trunk motion on landing kinematics and kinetics in a lab setting. Active trunk flexion increased peak knee and hip flexion and reduced vertical ground reaction forces (GRF) and quadriceps activation during a double-leg landing (Blackburn & Padua, 2008). Added trunk-load increased estimated knee anterior shear forces in participants who increased trunk extension but not in participants who increased trunk flexion in a double-leg landing (Kulas, Hortobagyi, & Devita, 2010). These two studies support that positioning the trunk centre of mass closer to the knee in the anterior-posterior direction is likely to decrease ACL loading (Blackburn & Padua, 2008; Kulas et al., 2010). In regard to trunk bending, Kimura et al. (2012) quantified single-left-legged landing mechanics after an overhead stroke following left or right back-stepping in female right-handed badminton players. The left back-stepping, which involved greater lateral trunk bending toward the left leg, resulted in increased knee abduction angles and moments compared to the right back-stepping. In addition, peak knee abduction moments were positively correlated with lateral trunk bending and rotation toward the landing leg in a single-leg landing after catching a ball (Dempsey, Elliott, Munro, Steele, & Lloyd, 2012). Furthermore, a side-step cutting study also found lateral trunk bending and rotation toward the cutting leg to increase knee abduction and internal rotation moments respectively (Dempsey et al., 2007). Recently, Hinshaw et al. (in press) showed mid-flight lateral trunk bending resulted in re-positioning of body segment centre of mass, and subsequently increased impact forces, knee internal rotation and abduction angles for the leg on the bending side. These four studies support the connection between lateral trunk bending and increased ACL loading (Dempsey et al., 2007; Dempsey et al., 2012; Hinshaw et al., in press; Kimura et al., 2012). Regarding trunk rotation, increased impact GRF and force couple indexes were observed when soccer players landed with two feet after mid-flight whole-body rotation (Harry, Barker, Mercer, & Dufek, 2017), but this study was limited to force analyses and whole-body rotation. A previous study has shown that individuals demonstrate decreased knee flexion angles and increased knee moments and knee valgus and internal rotation angles when the testing leg is placed on the lateral side of the jumping direction during an anticipated landing-lateral-jump task, suggesting the two legs may load differently during a horizontal landing task (Stephenson et al., 2018). However, the effects of whole-body and trunk rotation on double-leg landing kinematics and kinetics are unknown. Studying double-leg landing is particularly important for identifying factors that may cause increased loading for one leg, as bilateral asymmetries have been identified as risk factors for ACL injuries (Hewett et al., 2005; Paterno et al., 2010).

Therefore, the purpose of the current study was to quantify the effects of mid-flight whole-body and trunk rotation on knee kinematics and kinetics in a double-leg landing in five conditions: no rotation, testing leg ipsilateral or contralateral to the whole-body rotation direction, and testing leg ipsilateral or contralateral to the trunk rotation direction. The whole-body rotation condition involved a forward jump with 90-degree whole-body rotation, which would place the leg contralateral to whole-body rotation to the lateral side of the landing direction. Based on the literature (Dempsey et al., 2012; Stephenson et al., 2018), it was hypothesised that the leg contralateral to whole-body rotation and the leg ipsilateral to the trunk rotation would demonstrate less knee flexion angles and greater landing forces, knee moments, and knee abduction and internal rotation angles compared to other three conditions.

Methods

Participants

Based on previous studies (Dempsey et al., 2012; Stephenson et al., 2018), a medium to large effect was expected for the comparisons between landings with or without rotation. Based on an effect size of 0.5 for a paired t-test, a sample size of 34 was needed to achieve a power of 0.8 at a type-I error level of 0.05. Eighteen males and twenty females volunteered to participate (age: 21.2 ± 2.3 years; height: 1.72 ± 0.10 m; mass: 72.0 ± 13.0 kg). Participants had experience in jump-landing sports or exercises and participated in sports or exercise at least two times for a total of 2-3 hours per week at the time of testing. Individuals were excluded if they (1) had a major lower extremity injury that required surgical treatment, (2) had a lower extremity injury that kept them from participating in physical activities for more than 2 weeks in the previous 6 months, (3) possessed any other conditions that prevent participation at maximum effort, or (4) were pregnant. This study was approved by the University of Wyoming Institutional Review Board. Participants signed informed consent forms prior to data collection.

Procedure

Data Collection was performed in a biomechanics lab. Participants performed a 5-minute jog and a standard dynamic stretching protocol (Dai et al., 2018). Spandex shirts and pants and standard shoes (Ghost 5, Brooks Sports Inc. Seattle, WA, USA) were provided. Retro-reflective markers were placed on the 7th cervical vertebra, superior sternum, left and right acromioclavicular joints, iliac crests, anterior superior iliac spines, posterior superior iliac spines, and greater trochanters. On the testing leg (preferred leg to jump for a further distance), markers were placed on the lateral and anterior mid-thigh, medial and lateral femoral condyles, tibial tuberosity, anterior inferior shank, lateral shank, medial and lateral malleolus, calcaneus, first toe, and first and fifth metatarsal heads.

After a static trial, participants completed a jump-landing-jump task in five conditions (Figure 1). For the no rotation (NR) condition (Figure 2), the participant jumped from a 30-cm box located half the participant's height away from the landing area. A standard men's basketball was located on a tripod at the participant's elbow height. The ball was placed half the participant's arm length directly in front of the participant's toes. For the two whole-body rotation conditions, the ball was placed at the same location as the NR condition, but the box placement was moved 90 degrees around the force platform. As such, the testing leg was either ipsilateral (WBRI, Figure 3) or contralateral (WBRC, Figure 4) to whole-body rotation direction.

For the two trunk rotation conditions, the box was placed at the same location as the NR condition, but the ball placement was moved 90 degrees around the force platform. Similarly, the testing leg was either ipsilateral (TRI, Figure 5) or contralateral (TRC, Figure 6) to the trunk rotational direction.

For all five conditions, participants were instructed to jump forward from the box, reach for and hold the basketball as early in the movement as possible, land with feet on the targeted area, then perform a maximum vertical jump. When jumping off the box, participants were instructed to minimise the height they jumped to reach the targeted landing area, but the exact jump height was not standardised. For the whole-body rotation conditions, participants rotated their whole-body after they jumped from the box and landed with both feet pointing to the same direction as the NR condition. For the trunk rotation condition, participants rotated their trunk to reach the ball while they landed with both feet pointing to the same direction as the NR condition. A trial was repeated if a participant failed to land on the targeted area, paused before performing the maximal vertical jump, or if there was a significant delay between reaching for the ball and landing. Participants had a minimum of two practice trials followed by three official trials for each condition. A minimum of 30-seconds rest between trials was given. The order of the five conditions was randomised for each participant. Kinematic data were recorded using eight Vicon Bonita 10 cameras at a sampling frequency of 160 Hz (Vicon Motion Systems Ltd, Oxford, UK). GRF data were collected using one Bertec FP4060-10 force platform at a sampling frequency of 1600 Hz (Bertec Corporation, Columbus, OH, USA).

****Figures 1-6 near here****

Data Reduction

GRF and kinematic data were filtered via a fourth-order, zero-phase Butterworth filter with a low-pass cutoff of 100 Hz and 15 Hz, respectively (Stephenson et al., 2018). Joint centres and segment reference frames for the pelvis and lower extremities were defined as previously described (Dai, Heinbaugh, Ning, & Zhu, 2014). A trunk reference frame was also defined by the left and right acromioclavicular joints and the centre of the anterior superior iliac spines and posterior superior iliac spines. Cardan angles with an order of rotation of flexion (+) /extension (-), adduction (+) / abduction (-), and internal (+) / external (-) rotation were calculated between the thigh and shank reference frames for knee joint angles, and between the trunk and pelvis reference frames for trunk joint angles. Joint angles during the static trials were subtracted from those during the jump-landing-jump trials. Joint resultant moments were calculated using an inverse dynamics approach (Kingma, de Looze, Toussaint, Klijnsma, & Bruijnen, 1996). Segment mass, centre of mass, and moments of inertia were based on a previous study (de Leva, 1996). Knee joint resultant moments were expressed in the tibia reference frames as internal moments. Joint moments were normalised by the participant's body weight and height. GRF were normalised by the participant's body weight.

Trunk rotation angles were assessed at initial contact and 100 ms after landing with the targeted rotational direction defined as positive. Similar to previous studies (Kristianslund & Krosshaug, 2013; Stephenson et al., 2018), both initial and peak knee flexion, abduction, and internal rotation angles during the first 100 ms of landing were identified. Peak vertical GRF, knee adduction, extension, and external rotation moments during the first 100 ms of landing were also extracted. Jump height and stance time were calculated to quantify jump performance (Dai et al., 2015). These calculations were performed using customised subroutines developed in MATLAB (MathWorks Inc. Natick, MA, USA).

Statistical Analysis

Data for the three official trials were averaged for analysis. Dependent variables were compared among the five jump-landing-jump conditions using repeated measures analyses of variance (ANOVA). Significant ANOVAs were then followed by paired t-tests. A type-I error rate of 0.05 was used for the ANOVAs for statistical significance. The study-wide false discovery rate for all the paired t-tests was controlled at 0.05 (Benjamini & Hochberg, 1995). The effect sizes of changes between two conditions were quantified using Cohen's dz, with Cohen's dz < 0.5 considered 'small,' $0.5 \leq$ Cohen's dz < 0.8 considered 'medium,' and Cohen's dz ≥ 0.8 considered 'large' (Cohen, 1988). Statistical tests were performed using SPSS Statistics 24 software (IBM Corporation, Armonk, NY, USA).

Results

Significant ANOVAs were found for all variables (Table 1, 2). The largest p value for a significant paired t-test was 0.033 after the adjustment for the false discovery rate. Jump height was significantly greater for the NR condition than the WBRC and TRC conditions with small effect sizes. The TRI and TRC conditions demonstrated significantly longer stance time and greater trunk rotation at both initial contact and 100 ms after landing than the other three conditions with mostly large effect sizes.

For landing kinematics, the WBRC and TRI conditions demonstrated significantly decreased knee flexion angles at initial contact with mostly small effect sizes and increased knee abduction angles at initial contact with large effect sizes compared to the other three conditions. On the other hand, the WBRI and TRC conditions showed knee adduction angles instead of knee abduction angles at initial contact. The TRI condition also showed significantly greater knee internal rotation angles at initial contact than the other conditions with large effect sizes, while the WBRI and TRC conditions demonstrated knee external rotation angles instead of knee internal rotation angles at initial contact. The WBRC condition had significantly less peak knee flexion angles during the 100 ms after landing than the other conditions with large effect sizes, while the WBRI and TRI condition showed significantly less peak knee flexion angles than the NR and TRC conditions with medium to large effect sizes. Peak knee abduction and internal rotation angles during the 100 ms after landing were the greatest for the TRI condition with medium to large effect sizes and the least for the WBRI and TRC conditions.

For landing kinetics, the WBRC and TRI conditions demonstrated significantly greater peak vertical GRF and knee adduction moments than the other three conditions with mostly medium to large effect sizes. The TRI condition also showed significantly greater knee extension moments than the other conditions with mostly large effect sizes. In contrast, the TRC condition showed the least peak vertical GRF and peak knee adduction moments, while the WBRI condition demonstrated the least peak knee extension and external rotation moments.

****Tables 1-2 near here****

Discussion and Implications

The purpose of the current study was to quantify the effect of mid-flight whole-body and trunk rotation on double-leg landing mechanics. Whole-body and trunk rotation was imposed by tasks that simulated catch and shoot manoeuvres in basketball and netball. The increased trunk rotation at initial contact and 100 ms after landing confirmed that trunk rotation was initiated in mid-flight and persisted during early landing for the trunk rotation conditions. On the other hand, the small trunk rotation angles for the whole-body rotation conditions suggested that the body was rotated together in mid-flight.

The results generally support the hypothesis that the leg contralateral to whole-body rotation and the leg ipsilateral to the trunk rotation would demonstrate less knee flexion angles and greater landing forces, knee moments, and knee abduction and internal rotation angles compared to other three conditions. The whole-body rotation condition was characterised by decreased knee flexion angles, increased knee abduction and internal rotation angles, and increased GRF and knee moments for the contralateral leg compared to the ipsilateral leg, associated with increased ACL loading for the contralateral leg (Dai et al., 2014). As the participants jumped forward, rotating the body 90 degrees in mid-flight, the two legs were placed parallel to the direction of the approaching velocity, resulting in a posture similar to a lateral landing. The preference for the contralateral leg to decelerate medial-lateral velocity was consistent with a previous study, showing individuals preferred to use the contralateral leg to land and generate a horizontal velocity in lateral jumps (Stephenson et al., 2018). For example, when a participant lands with an approaching velocity directed toward the right, the right leg is more likely to play a dominant role in generating a deceleration toward the left. This limb preference could be caused by stronger hip abductors than hip adductors (Sugimoto, Mattacola, Mullineaux, Palmer, & Hewett, 2014), as the medial-lateral decelerating force would impose internal hip abduction moments for the contralateral leg and hip adduction moments for the ipsilateral leg. A previous study has shown greater GRF and force couple indexes during landings with 180-degree whole-body rotation compared to landing without rotation (Harry et al., 2017). However, participants only jumped vertically without a horizontal velocity, and the individual role of the two legs was unclear. The current findings suggest that whole-body rotation may not affect the two legs equally. A forward jump with 90-degree whole-body rotation would impose greater loading for the leg that was mainly used for decelerating the medial-lateral velocity.

For the trunk rotation conditions, the ipsilateral leg in the trunk rotation condition experienced the greatest knee abduction and internal rotation angles as well as peak vertical GRF and knee moments, associated with increased ACL loading from all three planes (Dai et al., 2014). As the participant rotated the trunk to the ipsilateral leg, a greater percentage of body weight was shifted to the testing leg resulting in increased vertical GRF and joint moments. In addition, an internal hip adduction moment was needed to maintain postural stability because more weight was placed on the lateral side of the ipsilateral hip. Consequently, an internal hip adduction moment likely moved the knee medially and increased knee abduction angles (Hewett & Myer, 2011). Meanwhile, as the trunk, pelvis, and lower extremities act as a kinetic chain in landing, trunk rotation could have increased external rotation of the ipsilateral femur relative to the global coordinate system. An externally rotated femur relative to the global coordinate system could have the same mechanical effect as an internally rotated tibia relative to the global coordinate system, contributing to increased local knee internal rotation angles. For the contralateral leg, these mechanical effects were reversed and could have resulted in opposite changes in knee kinematics and kinetics. These findings are consistent with previous studies, showing increased trunk rotation to the supporting leg would increase external knee abduction or internal rotation moments in a single-leg landing or cutting manoeuvres (Dempsey et al., 2007;

Dempsey et al., 2012). The current study differed from previous studies by using a double-leg landing and showing that trunk rotation can cause different landing patterns for the two legs.

Previous studies have generally observed small knee flexion and increased knee abduction for ACL injuries, but the presence of knee internal or external rotation is less consistent (Krosshaug et al., 2007; Olsen et al., 2004; Stuelcken et al., 2016). One reason could be the difficulty in determining the time of injury and magnitude of knee rotation from uncalibrated cameras (Dai et al., 2015; Koga et al., 2010). To improve the validity of video analyses, Koga et al. (2010) used a model-based image-matching method to quantify knee kinematics for ACL injuries. Small knee flexion angles along with increases in knee abduction and internal rotation were found during the first 40 ms after landing. However, the knee started to rotate externally after the injury. An *in vitro* study has also shown that the knee changed from internal rotation to external rotation after the ACL is ruptured under compressive loads (Meyer & Haut, 2008). Therefore, the knee external rotation observed in some studies might be the consequences instead of the causes of ACL injuries (Meyer & Haut, 2008). Kim et al. (2015) used bone bruise location on the femur and tibia to reconstruct knee kinematics near the time of ACL injuries. The injured knee was close to full extension with a 5-degree increase in abduction, a 15-degree increase in internal rotation, and a 2.2-cm increase in anterior tibial translation compared to a neutral position. In addition, an *in vivo* study has shown that knee valgus collapse, mainly characterised by increased knee external rotation, decreased ACL length (Utturkar et al., 2013). These findings also support knee internal rotation being more likely to contribute to ACL injuries than knee external rotation. However, two studies have observed that the trunk was more likely to rotate away from the injured leg and resulted in knee external rotation when ACL injuries occur (Stuelcken et al., 2016; Walden et al., 2015). This inconsistency could result from the limitations of qualitative video analyses, as no calibration was performed for accurately quantifying joint angles. Even with the previously mentioned image-matching technique for analysing ACL injury videos, the root mean square of differences in knee internal/external rotation in side-cutting was still around 10 degrees compared to a motion capture system with skin-mounted markers (Krosshaug & Bahr, 2005). Meanwhile, another explanation could be that knee internal rotation may not be a necessary factor in ACL injuries if excessive loads from other mechanisms are present. In the current study, the ipsilateral knee kinematics for the trunk rotation conditions resemble the injured knee position reconstructed with a high accuracy (Kim et al., 2015). Trunk motion provides a proximal-distal mechanism for knee internal rotation when the foot is typically fixed on the ground and rotated outward relative to the global coordinate system in landing. Future studies are needed to quantify trunk and lower extremity rotation with a high accuracy to further elucidate the role of trunk rotation in ACL injury events.

Several strategies may be utilised to modify factors associate with ACL loading when landing after whole-body and trunk rotation. After completing a task that involved mid-flight trunk rotation, individuals are encouraged to return to a neutral trunk position before landing. Second, individuals should have adequate proprioceptive awareness and increase both knee and hip flexion in mid-flight when whole-body or trunk rotation occurs. This strategy will increase the flight time for adjusting trunk position and preparing for a soft landing. Third, avoiding landing with excessive whole-body and trunk rotation may be considered for individuals whose priority during sports participation is not performance.

There were several limitations to the current study. First, the power analysis was performed for comparisons of different jump-landing conditions in both males and females without considering potential sex effects or interactions. Our secondary analyses including sex as an independent variable showed minimal sex effects and interactions for knee kinematics and kinetics, suggesting males and females responded similarly to trunk and whole-body rotation. Second, only the dominant leg was tested, and bilateral asymmetries were not directly quantified. Dominant and non-dominant legs were assumed to demonstrate similar landing patterns among different conditions, and leg dominance may have affected some side-to-side differences. Third, considering the injury knee at the estimated time of ACL injury only had a 5-degree increase in abduction and a 15-degree increase in internal rotation (Kim et al., 2015), increases of 2-3 degrees in these angles with medium to large effect sizes were likely to be clinically significant in the current study. However, previous studies have documented significant errors of using motion capture systems with skin-mounted markers for quantifying knee joint angles in the frontal and transverse planes compared to bone-mounted markers or biplanar fluoroscopy techniques (Benoit et al., 2006; Miranda, Rainbow, Crisco, & Fleming, 2013). Future studies are needed to quantify more accurate femur and tibia motion associated with trunk and whole-body rotation during landing. Fourth, the current task was an anticipated task. An examination without a pre-planned condition could investigate the role that trunk rotation plays on landing mechanics in a more game-like setting. Fixed ball locations were used to prevent excessive whole-body and trunk rotation. Increasing rotation may induce greater changes in landing mechanics but may also raise safety concerns. In addition, the whole-body rotation condition resulted in a lateral landing, so it was not possible to separate the effect of the lateral deceleration from that of the deceleration of the whole-body rotation. Last, the findings can only be applied to individuals without major injuries. Including individuals with a history of ACL injuries may reveal different landing patterns and help understand secondary ACL injuries.

Conclusions

Whole-body rotation increased contralateral knee loading because of its primary role in decelerating medial-lateral velocities. Trunk rotation resulted in the greatest loading for the ipsilateral knee due to weight shifting and mechanical coupling between the trunk, pelvis, and lower extremities. The kinematics demonstrated by the ipsilateral knee with trunk rotation resemble knee positions near the time of ACL injuries. These findings may help researchers better understand trunk rotation in ACL injury events. Athletes should be aware that mid-flight whole-body and trunk rotation may result in increased loading for one leg. Specific technique and neuromuscular training may help athletes better prepare for these situations.

Disclosure of funding

The current study was supported by a student research grant from the College of Health Sciences at the University of Wyoming. Jacob Layer's graduate assistantship was provided by the Wyoming INBRE, which was supported by a grant from the National Institute of General Medical Sciences (P20GM103432) from the National Institutes of Health.

References

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society, Series B, 57*, 289-300.

Benoit, D. L., Ramsey, D. K., Lamontagne, M., Xu, L., Wretenberg, P., & Renstrom, P. (2006). Effect of skin movement artifact on knee kinematics during gait and cutting motions measured in vivo. *Gait & Posture, 24*, 152-164.

Blackburn, J. T., & Padua, D. A. (2008). Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clinical Biomechanics, 23*, 313-319. doi:10.1016/j.clinbiomech.2007.10.003

Cohen, J. (1988). The T-Test for Means. In: *Statistical power analysis for the behavioural sciences*. pp. 25–48. Hillsdale, NJ: Lawrence Erlbaum Associates.

Dai, B., Garrett, W. E., Gross, M. T., Padua, D. A., Queen, R. M., & Yu, B. (2015). The effects of 2 landing techniques on knee kinematics, kinetics, and performance during stop-jump and side-cutting tasks. *The American Journal of Sports Medicine, 43*, 466-474. doi:10.1177/0363546514555322

Dai, B., Heinbaugh, E. M., Ning, X., & Zhu, Q. (2014). A resistance band increased internal hip abduction moments and gluteus medius activation during pre-landing and early-landing. *Journal of Biomechanics, 47*, 3674-3680. doi:10.1016/j.jbiomech.2014.09.032

Dai, B., Hinshaw, T. J., Trumble, T. A., Wang, C., Ning, X., & Zhu, Q. (2018). Lowering minimum eye height to increase peak knee and hip flexion during landing. *Research in Sports Medicine, 26*, 251-261. doi:10.1080/15438627.2018.1447477

Dai, B., Mao, D., Garrett, W. E., & Yu, B. (2014). Anterior cruciate ligament injuries in soccer: Loading mechanisms, risk factors, and prevention programs. *Journal of Sport and Health Science, 3*, 299-306. doi:10.1016/j.jshs.2014.06.002

Dai, B., Mao, M., Garrett, W. E., & Yu, B. (2015). Biomechanical characteristics of an anterior cruciate ligament injury in javelin throwing. *Journal of Sport and Health Science, 4*, 333-340. doi:10.1016/j.jshs.2015.07.004

de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics, 29*, 1223-1230.

Dempsey, A. R., Elliott, B. C., Munro, B. J., Steele, J. R., & Lloyd, D. G. (2012). Whole body kinematics and knee moments that occur during an overhead catch and landing task in sport. *Clinical Biomechanics, 27*, 466-474. doi:10.1016/j.clinbiomech.2011.12.001

Dempsey, A. R., Lloyd, D. G., Elliott, B. C., Steele, J. R., Munro, B. J., & Russo, K. A. (2007). The effect of technique change on knee loads during sidestep cutting. *Medicine and Science in Sports and Exercise, 39*, 1765-1773. doi:10.1249/mss.0b013e31812f56d1

DiStefano, L. J., Padua, D. A., DiStefano, M. J., & Marshall, S. W. (2009). Influence of age, sex, technique, and exercise program on movement patterns after an anterior cruciate ligament injury prevention program in youth soccer players. *The American Journal of Sports Medicine, 37*, 495-505. doi:10.1177/0363546508327542

Gianotti, S. M., Marshall, S. W., Hume, P. A., & Bunt, L. (2009). Incidence of anterior cruciate ligament injury and other knee ligament injuries: A national population-based study. *Journal of Science and Medicine in Sport, 12*, 622-627. doi:10.1016/j.jsams.2008.07.005

Granan, L. P., Bahr, R., Steindal, K., Furnes, O., & Engebretsen, L. (2008). Development of a national cruciate ligament surgery registry: The Norwegian national knee ligament registry. *The American Journal of Sports Medicine, 36*, 308-315. doi:10.1177/0363546507308939

Harry, J. R., Barker, L. A., Mercer, J. A., & Dufek, J. S. (2017). Vertical and horizontal impact force comparison during jump landings with and without rotation in NCAA division I male soccer players. *Journal of Strength and Conditioning Research, 31*, 1780-1786. doi:10.1519/JSC.0000000000001650

Hewett, T. E., & Myer, G. D. (2011). The mechanistic connection between the trunk, hip, knee, and anterior cruciate ligament injury. *Exercise and Sport Sciences Reviews, 39*, 161-166. doi:10.1097/JES.0b013e3182297439

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S.,Jr, Colosimo, A. J., McLean, S. G., . . . Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *The American Journal of Sports Medicine, 33*, 492-501. doi:10.1177/0363546504269591

Hewett, T. E., Torg, J. S., & Boden, B. P. (2009). Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: Lateral trunk and knee abduction motion are combined components of the injury mechanism. *British Journal of Sports Medicine, 43*, 417-422. doi:10.1136/bjsm.2009.059162

Hinshaw, T. J., Davis, D. J., Layer, J. S., Wilson, M. A., Zhu, Q., & Dai, B. (in press). Mid-flight lateral trunk bending increased ipsilateral leg loading during landing: A center of mass analysis. *Journal of Sports Sciences*. doi:10.1080/02640414.2018.1504616

Ingersoll, C. D., Grindstaff, T. L., Pietrosimone, B. G., & Hart, J. M. (2008). Neuromuscular consequences of anterior cruciate ligament injury. *Clinics in Sports Medicine, 27*, 383-404, vii. doi:10.1016/j.csm.2008.03.004

Kamath, G. V., Murphy, T., Creighton, R. A., Viradia, N., Taft, T. N., & Spang, J. T. (2014). Anterior cruciate ligament injury, return to play, and reinjury in the elite collegiate athlete: Analysis of an NCAA division I cohort. *The American Journal of Sports Medicine, 42*, 1638-1643. doi:10.1177/0363546514524164

Kay, M. C., Register-Mihalik, J. K., Gray, A. D., Djoko, A., Dompier, T. P., & Kerr, Z. Y. (2017). The epidemiology of severe injuries sustained by national collegiate athletic association student-athletes, 2009-2010 through 2014-2015. *Journal of Athletic Training, 52*, 117-128. doi:10.4085/1062-6050-52.1.01

Kim, S. Y., Spritzer, C. E., Utturkar, G. M., Toth, A. P., Garrett, W. E., & DeFrate, L. E. (2015). Knee kinematics during noncontact anterior cruciate ligament injury as determined from bone bruise location. *The American Journal of Sports Medicine, 43*, 2515-2521. doi:10.1177/0363546515594446

Kimura, Y., Ishibashi, Y., Tsuda, E., Yamamoto, Y., Hayashi, Y., & Sato, S. (2012). Increased knee valgus alignment and moment during single-leg landing after overhead stroke as a potential risk factor of anterior cruciate ligament injury in badminton. *British Journal of Sports Medicine, 46*, 207-213. doi:10.1136/bjsm.2010.080861

Kingma, I., de Looze, M. P., Toussaint, H. M., Klijnsma, H. G., & Bruijnen, T. B. M. (1996). Validation of a full body 3-D dynamic linked segment model. *Human Movement Science, 15*, 833-860. doi:10.1016/S0167-9457(96)00034-6

Koga, H., Nakamae, A., Shima, Y., Iwasa, J., Myklebust, G., Engebretsen, L., . . . Krosshaug, T. (2010). Mechanisms for noncontact anterior cruciate ligament injuries: Knee joint kinematics in 10 injury situations from female team handball and basketball. *The American Journal of Sports Medicine, 38*, 2218-2225. doi:10.1177/0363546510373570

Kristianslund, E., & Krosshaug, T. (2013). Comparison of drop jumps and sport-specific sidestep cutting: Implications for anterior cruciate ligament injury risk screening. *The American Journal of Sports Medicine, 41*, 684-688. doi:10.1177/0363546512472043

Krosshaug, T., & Bahr, R. (2005). A model-based image-matching technique for three-dimensional reconstruction of human motion from uncalibrated video sequences. *Journal of Biomechanics, 38*, 919-929. doi:10.1016/j.jbiomech.2004.04.033

Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterbeck, J. R., . . . Bahr, R. (2007). Mechanisms of anterior cruciate ligament injury in basketball: Video analysis of 39 cases. *The American Journal of Sports Medicine, 35*, 359-367. doi:10.1177/0363546506293899

Kulas, A. S., Hortobagyi, T., & Devita, P. (2010). The interaction of trunk-load and trunk-position adaptations on knee anterior shear and hamstrings muscle forces during landing. *Journal of Athletic Training, 45*, 5-15. doi:10.4085/1062-6050-45.1.5

Luc, B., Gribble, P. A., & Pietrosimone, B. G. (2014). Osteoarthritis prevalence following anterior cruciate ligament reconstruction: A systematic review and numbers-needed-to-treat analysis. *Journal of Athletic Training, 49*, 806-819. doi:10.4085/1062-6050-49.3.35

Meyer, E. G., & Haut, R. C. (2008). Anterior cruciate ligament injury induced by internal tibial torsion or tibiofemoral compression. *Journal of Biomechanics, 41*, 3377-3383. doi:10.1016/j.jbiomech.2008.09.023

Miranda, D. L., Rainbow, M. J., Crisco, J. J., & Fleming, B. C. (2013). Kinematic differences between optical motion capture and biplanar videoradiography during a jump-cut maneuver. *Journal of Biomechanics, 46*, 567-573. doi:10.1016/j.jbiomech.2012.09.023

Olsen, O. E., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball: A systematic video analysis. *The American Journal of Sports Medicine, 32*, 1002-1012.

Paterno, M. V., Schmitt, L. C., Ford, K. R., Rauh, M. J., Myer, G. D., Huang, B., & Hewett, T. E. (2010). Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *The American Journal of Sports Medicine, 38*, 1968-1978. doi:10.1177/0363546510376053

Sheehan, F. T., Sipprell, W. H.,3rd, & Boden, B. P. (2012). Dynamic sagittal plane trunk control during anterior cruciate ligament injury. *The American Journal of Sports Medicine, 40*, 1068-1074. doi:10.1177/0363546512437850

Stephenson, M. L., Hinshaw, T. J., Wadley, H. A., Zhu, Q., Wilson, M. A., Byra, M., & Dai, B. (2018). Effects of timing of signal indicating jump directions on knee biomechanics in jump-landing-jump tasks. *Sports Biomechanics, 17*, 67-82. doi:10.1080/14763141.2017.1346141

Stuelcken, M. C., Mellifont, D. B., Gorman, A. D., & Sayers, M. G. (2016). Mechanisms of anterior cruciate ligament injuries in elite women's netball: A systematic video analysis. *Journal of Sports Sciences, 34*, 1516-1522. doi:10.1080/02640414.2015.1121285

Sugimoto, D., Mattacola, C. G., Mullineaux, D. R., Palmer, T. G., & Hewett, T. E. (2014). Comparison of isokinetic hip abduction and adduction peak torques and ratio between sexes. *Clinical Journal of Sport Medicine, 24*, 422-428. doi:10.1097/JSM.0000000000000059

Utturkar, G. M., Irribarra, L. A., Taylor, K. A., Spritzer, C. E., Taylor, D. C., Garrett, W. E., & Defrate, L. E. (2013). The effects of a valgus collapse knee position on in vivo ACL elongation. *Annals of Biomedical Engineering, 41*, 123-130. doi:10.1007/s10439-012-0629-x; 10.1007/s10439-012-0629-x

Walden, M., Krosshaug, T., Bjorneboe, J., Andersen, T. E., Faul, O., & Hagglund, M. (2015). Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: A systematic video analysis of 39 cases. *British Journal of Sports Medicine, 49*, 1452-1460. doi:10.1136/bjsports-2014-094573

Welling, W., Benjaminse, A., Gokeler, A., & Otten, B. (2016). Enhanced retention of drop vertical jump landing technique: A randomized controlled trial. *Human Movement Science, 45*, 84-95. doi:10.1016/j.humov.2015.11.008

Zazulak, B. T., Hewett, T. E., Reeves, N. P., Goldberg, B., & Cholewicki, J. (2007). Deficits in neuromuscular control of the trunk predict knee injury risk: A prospective biomechanical-epidemiologic study. *The American Journal of Sports Medicine, 35*, 1123-1130. doi:10.1177/0363546507301585

Figure captions

Figure 1. Top view of the design of the five jump-landing-jump tasks. The left leg was the testing leg.

Figure 2. Landing without mid-flight rotation (takeoff, initial landing, maximum knee flexion, maximum jump height). The left leg was the testing leg.

Figure 3. Landing with mid-flight whole-body rotation to the testing leg (takeoff, initial landing, maximum knee flexion, maximum jump height). The left leg was the testing leg and acted as the ipsilateral leg.

Figure 4. Landing with mid-flight whole-body rotation away from the testing leg (takeoff, initial landing, maximum knee flexion, maximum jump height). The left leg was the testing leg and acted as the contralateral leg.

Figure 5. Landing with mid-flight trunk rotation to the testing leg (takeoff, initial landing, maximum knee flexion, maximum jump height). The left leg was the testing leg and acted as the ipsilateral leg.

Figure 6. Landing with mid-flight trunk rotation away from the testing leg (takeoff, initial landing, maximum knee flexion, maximum jump height). The left leg was the testing leg and acted as the contralateral leg.

Table 1. Means ± standard deviation of dependent variables for five jump-landing-jump conditions.

	NR	WBRI	WBRC	TRI	TRC	p values of ANOVA
Jump height (m)	0.38 ± 0.11 A	0.37 ± 0.11 AB	0.37 ± 0.10 B	0.37 ± 0.10 AB	0.37 ± 0.11 B	0.039
Stance time (ms)	501.8 ± 70.3 C	542.0 ± 74.9 B	483.8 ± 96.4 C	578.8 ± 108.4 A	572.8 ± 100.1 A	<0.001
Trunk rotation angles at initial contact (°)	0.2 ± 3.7 B	-4.7 ± 4.8 C	-8.9 ± 4.9 D	28.6 ± 7.6 A	27.6 ± 6.5 A	<0.001
Trunk rotation angles at 100 ms after landing (°)	0.4 ± 3.3 B	-5.8 ± 4.0 C	-4.5 ± 4.1 C	29.7 ± 5.7 A	27.5 ± 5.7 A	<0.001
Knee flexion angles (+) at initial contact (°)	20.5 ± 6.6 A	20.1 ± 5.9 A	18.1 ± 6.7 BC	18.1 ± 4.9 C	20.2 ± 6.9 AB	0.002
Knee adduction (+) / abduction angles (-) at initial contact (°)	0.1 ± 2.6 B	1.7 ± 2.6 C	-1.9 ± 2.2 A	-2.0 ± 2.4 A	1.9 ± 3.4 C	<0.001
Knee internal (+) / external (-) rotation angles at initial contact (°)	0.2 ± 4.9 B	-3.2 ± 5.3 C	-0.3 ± 4.6 B	3.5 ± 5.6 A	-2.6 ± 4.9 C	<0.001
Peak knee flexion angles (+) during 100 ms after landing (°)	77.7 ± 7.3 A	74.8 ± 6.4 B	69.5 ± 7.4 C	74.6 ± 6.7 B	77.5 ± 7.5 A	<0.001
Peak knee abduction angles (-) during 100 ms after landing (°)	-3.5 ± 5.0 BC	-2.9 ± 5.4 C	-4.2 ± 4.3 B	-6.2 ± 5.3 A	-0.9 ± 5.3 D	<0.001
Peak knee internal rotation (+) angles during 100 ms after landing (°)	8.0 ± 5.0 B	4.0 ± 4.9 D	8.0 ± 5.3 B	9.8 ± 5.6 A	6.7 ± 5.0 C	<0.001
Peak vertical ground reaction force during 100 ms after landing (BW)	2.2 ± 0.6 B	2.2 ± 0.4 B	2.5 ± 0.6 A	2.6 ± 0.6 A	1.9 ± 0.6 C	<0.001
Peak knee extension moments (-) during 100 ms after landing (BW*BH)	-0.11 ± 0.02 B	-0.09 ± 0.02 C	-0.11 ± 0.03 B	-0.12 ± 0.02 A	-0.11 ± 0.02 B	<0.001
Peak knee adduction moments (+) during 100 ms after landing (BW*BH)	0.04 ± 0.02 B	0.04 ± 0.02 B	0.05 ± 0.02 A	0.05 ± 0.02 A	0.03 ± 0.02 C	<0.001
Peak knee external rotation (-) moments during 100 ms after landing (BW*BH)	-0.004 ± 0.004 AB	-0.003 ± 0.004 B	-0.005 ± 0.004 A	-0.005 ± 0.004 A	-0.004 ± 0.004 A	0.049

Note: NR: no rotation; WBRI: testing leg on the ipsilateral side of the whole-body rotation; WBRC: testing leg on the contralateral side of the whole-body rotation; TRI: testing leg on the ipsilateral side of the trunk rotation; TRC: testing leg on the contralateral side of the trunk rotation; BW: body weight; BH: body height. The effect of landing condition is grouped, where A > B > C > D at a false discovery rate of 0.05.

Table 2. Cohen's dz of changes in dependent variables between each pair of jump-landing-jump conditions.

	NR vs. WBRI	NR vs. WBRC	NR vs. TRI	NR vs. TRC	WBRI vs. WBRC	WBRI vs. TRI	WBRI vs. TRC	WBRC vs. TRI	WBRC vs. TRC	TRI vs. TRC
Jump height	0.23	0.46	0.26	0.41	0.32	0.07	0.22	0.20	0.13	0.09
Stance time	0.74	0.29	1.06	1.05	0.86	0.52	0.38	1.23	1.14	0.09
Trunk rotation angles at initial contact	0.98	1.23	3.79	3.55	0.54	4.48	3.76	3.49	4.98	0.11
Trunk rotation angles at 100 ms after landing	1.61	0.81	5.05	4.36	0.20	7.10	4.51	4.02	4.71	0.30
Knee flexion angles at initial contact	0.11	0.53	0.50	0.08	0.38	0.48	0.02	0.00	0.34	0.40
Knee abduction angles at initial contact	1.12	1.35	1.87	1.21	2.08	2.51	0.10	0.11	2.02	2.42
Knee internal rotation angles at initial contact	0.97	0.16	1.04	0.75	0.69	1.93	0.14	1.26	0.50	1.47
Peak knee flexion angles during 100 ms after landing	0.67	2.14	0.97	0.08	1.27	0.08	0.69	1.04	1.59	1.02
Peak knee abduction angles during 100 ms after landing	0.29	0.28	1.09	1.53	0.50	1.18	0.97	0.80	1.45	1.96
Peak knee internal rotation angles during 100 ms after landing	1.25	0.02	0.58	0.54	1.09	1.60	0.92	0.66	0.38	0.94
Peak vertical ground reaction force during 100 ms after landing	0.04	0.72	1.10	0.47	0.54	0.84	0.46	0.31	0.93	1.08
Peak knee extension moments during 100 ms after landing	1.36	0.11	1.10	0.14	1.32	1.68	1.56	0.47	0.21	0.93
Peak knee adduction moments during 100 ms after landing	0.30	0.74	1.31	0.59	0.37	0.51	0.68	0.14	1.10	1.66
Peak knee external rotation moments during 100 ms after landing (BW*BH)	0.30	0.13	0.20	0.13	0.37	0.47	0.36	0.07	0.03	0.08

Note: NR: no rotation; WBRI: testing leg on the ipsilateral side of the whole-body rotation; WBRC: testing leg on the contralateral side of the whole-body rotation; TRI: testing leg on the ipsilateral side of the trunk rotation; TRC: testing leg on the contralateral side of the trunk rotation.

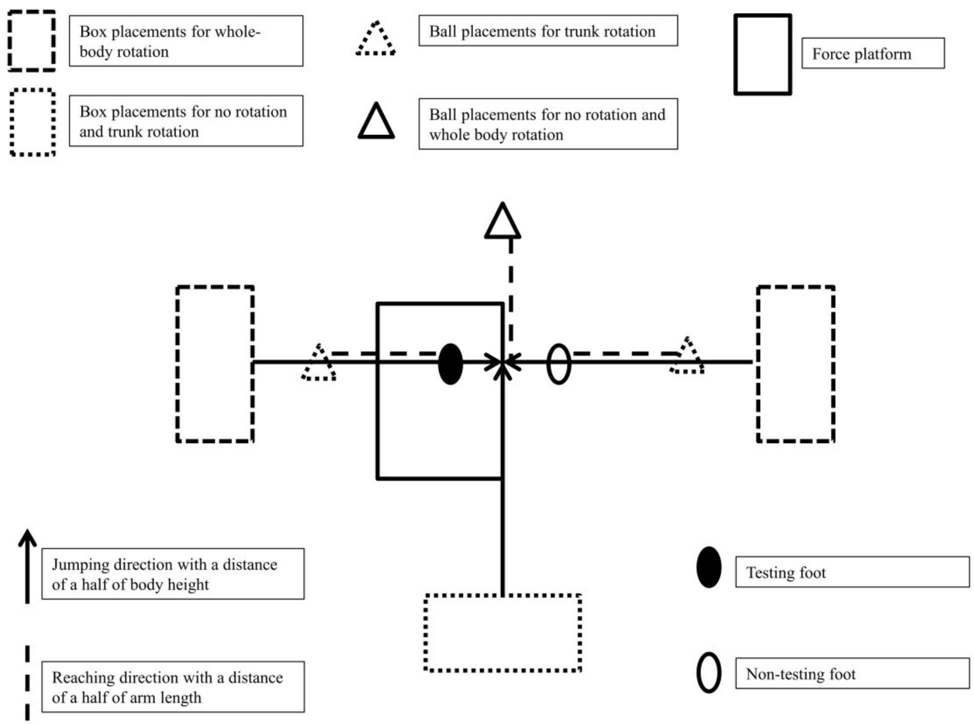

Figure 1

254x190mm (300 x 300 DPI)

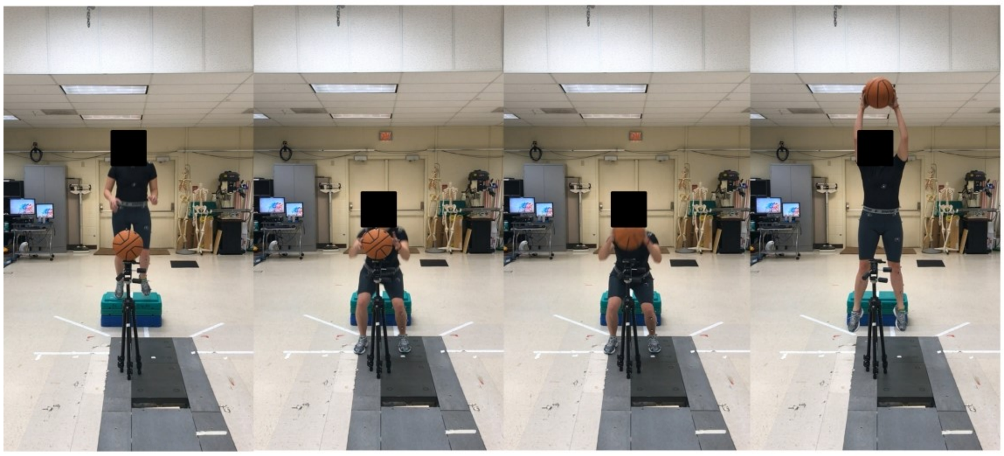

Figure 2

254x190mm (300 x 300 DPI)

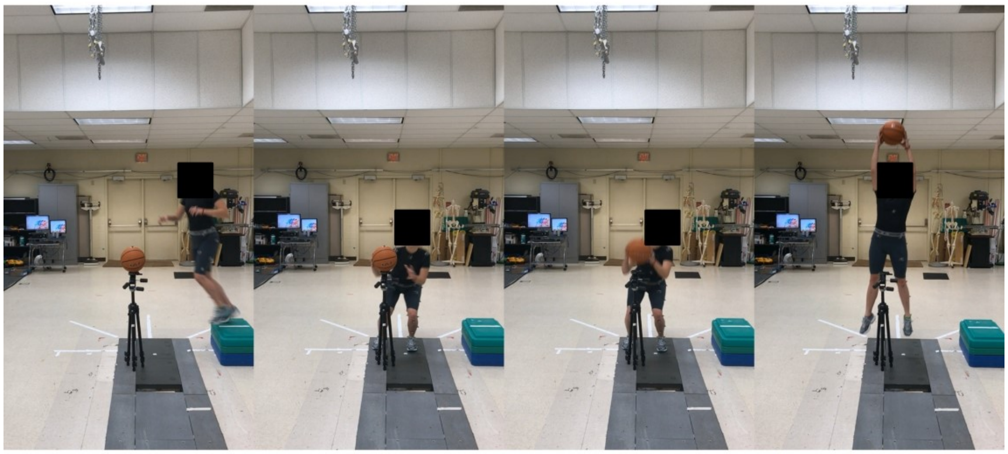

Figure 3

254x190mm (300 x 300 DPI)

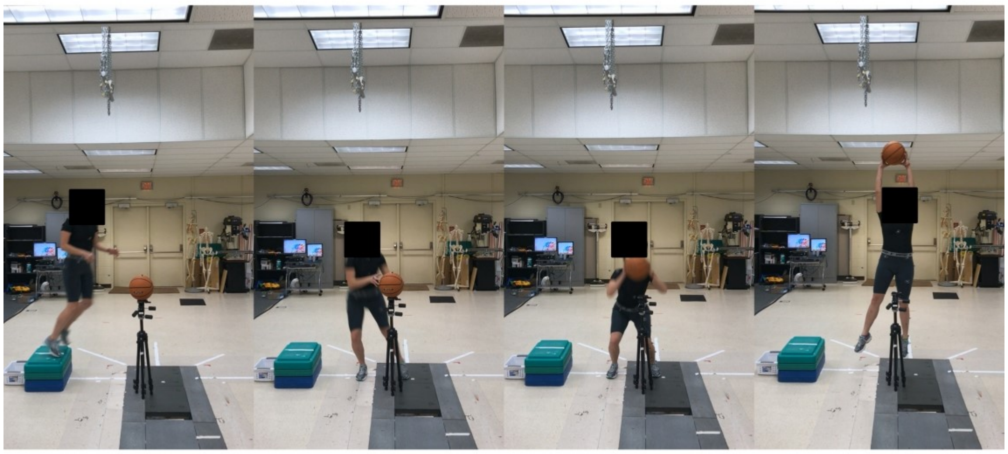

Figure 4

254x190mm (300 x 300 DPI)

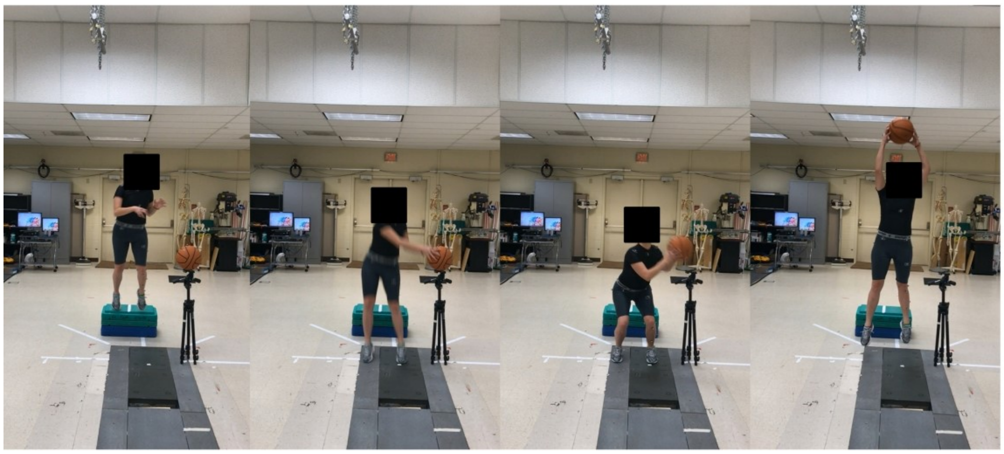

Figure 5

254x190mm (300 x 300 DPI)

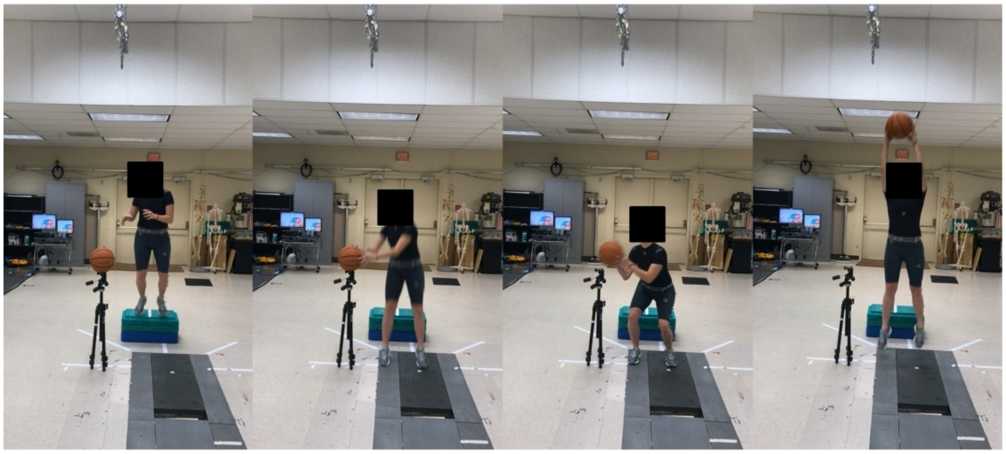

Figure 6

254x190mm (300 x 300 DPI)