Martonick NJ, Chun Y, Krumpl L, Bailey JP. Lower Extremity Kinematic Waveform Analysis During a Single Leg Drop Task – Including a Single Subject Design. *IJSPT*. 2022;17(7):1271-1281.

Original Research

Lower Extremity Kinematic Waveform Analysis During a Single Leg Drop Task – Including a Single Subject Design

Nickolai JP Martonick[1] [a], Youngmin Chun[2], Lukas Krumpl[1], Joshua P Bailey[1]

[1] Department of Movement Sciences, University of Idaho, [2] Department of Kinesiology, Sonoma State University

Keywords: Drop Landing, Single Subjects, Statistical Parametric Mapping, Lower Limb Asymmetry

https://doi.org/10.26603/001c.55538

International Journal of Sports Physical Therapy

Vol. 17, Issue 7, 2022

BACKGROUND

Lower limb asymmetries may be associated with increased injury risk in an active female population. However, an appropriate method for determining these asymmetries has not been established.

HYPOTHESIS/PURPOSE

The purpose of the present study was to examine the single leg drop landing (SLD) kinematic waveforms of female recreational athletes for the pelvis, hip, and knee using statistical parametric mapping (SPM). It was hypothesized that individual bilateral differences would be masked by the group analysis.

STUDY DESIGN

Descriptive Laboratory Study.

METHODS

The current study examined the sagittal and frontal plane pelvis, hip, and knee kinematics of nine physically active females during a SLD. To better elucidate whether asymmetries were present between right and left limbs throughout the landing phase, data were analyzed with SPM. The time-series data were comprised from initial contact to the bottom of the landing. A single subject design was also included to account for potential interindividual variability.

RESULTS

At the group level there were no statistical differences between the right and left limbs of participants for all variables. The single subject design yielded at least two significant asymmetries for all participants. Six out of the nine participants had bilateral differences for all six kinematic time-series.

CONCLUSIONS

The lack of significant differences at the group level may have been masked by movement variability amongst participants. For example, when considering participants with significant differences for hip flexion, four participants had greater values on the left limb and three on the right. A similar observation was made for knee flexion where three participants had significantly greater kinematic values on the left versus four on the right. Until a method is developed to adequately dichotomize lower extremities during the SLD task, a single subject design strategy be used with group analysis when making bilateral comparisons.

a **Corresponding author:**
Nickolai JP Martonick
University of Idaho, Department of Movement Sciences,
Moscow ID 83843
nmartonick@uidaho.edu

LEVEL OF EVIDENCE

3

INTRODUCTION

Landing on a single leg is a common movement in sports such as basketball, volleyball, and soccer. When this movement is not adequately controlled by the neuromuscular system, non-contact anterior cruciate ligament (ACL) injury may occur.[1,2] It is well established that female athletes are more likely to suffer non-contact ACL injuries than male counterparts participating in the same sports.[3] Female athletes have also been shown to have an increased propensity to experience ACL injury on their non-dominant limb which was defined as the stance limb when kicking a ball.[4,5] However, minimal differences in mechanical variables have been reported between dominant and non-dominant limbs during a cutting task in female soccer athletes.[6] Thus, it is unclear whether the reported increase in injury rate between dominant and non-dominant limbs are linked to bilateral mechanical differences.

Mechanisms for non-contact ACL injury consist of dynamic joint angles that result in excessive tensile forces on the ligament. For example, excessive knee abduction, and internal rotation have been shown to increase ACL strain during cadaveric modeling.[7] Video analysis of ACL injury incidents has identified combined knee abduction and internal rotation as a mechanism of injury.[8] Investigators have also demonstrated an increased lateral pelvic tilt is related to increased knee abduction moments, which may increase the risk of non-contact ACL injury.[1,9,10] Alternatively, studies using 3D modeling and magnetic resonance imaging suggest that the ACL is under greatest strain during knee extension during dynamic and static loading.[11,12] In addition to the various mechanisms of ACL injury, researchers have also hypothesized that lower extremity kinematic differences (asymmetry) can increase the risk for injury due to an increased loading and reliance on one limb, combined with an inability to maintain stability on the other.[13]

The single leg drop-landing (SLD) task is often used to assess lower limb kinematic symmetry.[14–16] Other tasks that are more functionally related to sport movements, including cutting maneuvers, single leg hop for distance, and single leg jumps, have also been used to analyze lower limb symmetry.[17–20] However, these tasks may require greater coordination and training to achieve or perform within the limits of a study design.[16] Thus, the relatively limited complexity of the SLD may make it advantageous for the analysis of intrinsic bilateral asymmetries across individuals with varied training backgrounds.

Previous studies that have used a SLD task to examine potential bilateral lower extremity asymmetries have reported mixed results. Recently, Wang and Fu demonstrated an increased total hip and knee range of motion in the sagittal plane in the dominant limb of female soccer players.[21] Other researchers[16] did not find bilateral kinematic hip and knee differences in recreationally active females. The differences between populations may explain the conflicting findings. However, another possible reason for the discrepancies between these studies is the classification of lower extremities by either *dominant limb* or *non-dominant limb* when performing a group analysis.

When using a group analysis for the examination of bilateral differences, problems may arise from the difficulty of classifying a dominant lower limb. While several studies have defined the dominant lower limb as the leg used to kick a ball,[5,6,14–16] limb dominance is likely task specific.[22] If limb dominance is task-specific, grouping participants' limbs based on what would be an arbitrary question, may generate misleading results. These factors have led researchers to contend that single subject design data should be reported in addition to group analysis when making bilateral comparisons.[23] Thus, reducing the potential for applicable findings to be masked by interindividual variability between dominant or non-dominant limbs.

Another potential reason for discrepancies between the aforementioned studies is the interpretation of variables at discrete time points which may lead to analysis of less than 5% of the data.[24] Discrete analysis of biomechanical variables may not always be comparable across participants or within participants due to temporal variations in movement traces.[18,25] These potential inconsistencies may limit the interpretation of a temporal component, and how kinematics temporally relate to other biomechanical factors within the same movement. Thus, a more robust method may be required when examining a movement related to ACL injury risk that does not have a clear mechanism and timing. A proposed solution to this problem is statistical parametric mapping (SPM) which can be used to statistically analyze the kinematic waveform of the complete task cycle.[25]

Bilateral asymmetries during a SLD have not been analyzed with a SPM analysis at the group or single subject level. Thus, the purpose of the present study was to examine the SLD kinematic waveforms of female recreational athletes for the pelvis, hip, and knee using SPM. By including a group analysis and single subject design, the current study sought to identify the potential of inter-participant variability to influence group bilateral asymmetries. It was hypothesized that bilateral differences of the waveforms at the single subject design level would occur but not at the group level due to inter-participant variability.

METHODS

PARTICIPANTS

Nine female participants who were free from lower limb surgery, disease, or current injury volunteered for this study. Participants had a mean [SD] age of 22.4 [3.5] years, height of 1.68 [0.57] m, mass of 61.0 [6.7] kg. All participants were defined as physically active and performed plyometric activities at least once per week. Physically active was defined as performing at least 30 minutes of low-in-

Figure 1. Custom cluster based model with calibration markers included.

tensity exercise five times per week, 20 minutes of high-intensity exercise three times per week, or participants who ran at least five miles per week. For descriptive purposes, all participants were asked which limb they preferred to kick a ball with. All reported that their right limb was their preferred kicking limb. Prior to participation, all participants signed an informed consent form approved by the University's internal review board.

INSTRUMENTATION

Three-dimensional marker trajectories were collected with an eight-camera motion capture system (250 Hz; VICON, Oxford Metric Ltd., Oxford, UK). Participants were equipped with 73 retro-reflective markers (14mm) used to create a custom cluster-based model for the upper extremities, torso, pelvis, and lower extremities (Figure 1).

A force-platform (1000 Hz; ORG-6, AMTI Inc., Watertown, MA, USA) time synchronized with the motion capture system was used to collect ground reaction forces (GRFs).

DROP LANDING PROCEDURE

Prior to performing the SLD, participants performed a five-minute warm-up on a stationary bicycle. Participants were then asked to perform the SLD task from a 60 cm platform after completing two practice trials on each leg. The platform was positioned behind the force platform with a minimum distance that allowed participants to vertically land on the center of the force platform to minimize GRF in the anteroposterior direction. Participants were asked to place the limb they would land on off the step and then drop down onto the force plate with minimal assistance from their stance limb to drop off the box. No restrictions were placed on the positioning of the arms. Participants performed 10 successful trials on each leg with a maximum of 15 attempts. Participants were given as much time as they needed between trials and the starting limbs were counterbalanced to reduce the potential effect of fatigue. Trials were considered successful if the participant was able to drop off the box without lowering themselves with the stance leg and maintain balance upon landing as determined by the researcher. All participants wore their own activity shoes, which was done to remove any perturbation caused by novel footwear.

DATA ANALYSIS

Angular kinematics and center of mass were computed using a Cardan (X-Y-Z) rotation sequence with Visual 3D software (v6, C-Motion Inc., Germantown, MD, USA). Pelvis segment angles were calculated using a Z-Y-X sequence of rotations to be consistent with the conventional clinical understanding of pelvic tilt and pelvic drop. The pelvis was modeled as a using the anterior and posterior superior iliac spines and pelvis segment angles were calculated relative to the global coordinate system. Pelvic drop was defined as the angle in the frontal plane and pelvic tilt was defined as the segment's rotation in the sagittal plane. Negative values in the frontal plane were represented as a contralateral pelvic drop and anterior pelvic tilt was represented by positive values. Marker trajectories were filtered using a fourth-order Butterworth filter at 8 Hz and kinetic data were filtered at 20 Hz respectively. Vertical GRF data was used to define initial contact (IC) at the beginning of the deceleration phase. The IC was defined as the moment when the vertical GRF threshold of 20 N was surpassed. To define the end of the deceleration phase, we used the minimum ver-

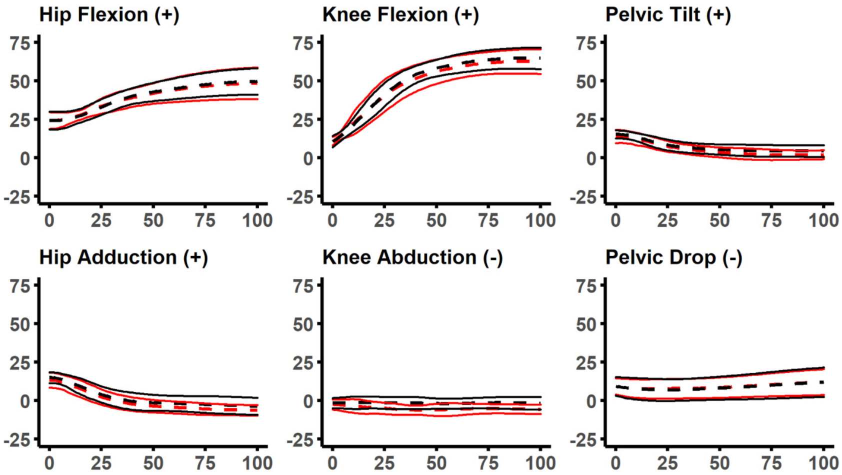

Figure 2. Group kinematics from initial contact to the minimum height of the center of mass.

Mean values are represented by dashed lines with the solid lines indicating standard deviations. The right limb is shown as black, and the left shown as red. Positive and negative values indicate the direction of the variable (e.g., (+) values indicate hip adduction and (-) values indicate hip abduction.

tical height of the center of mass (minCOM).[26] Joint (hip and knee) and segment (pelvis) temporal data were analyzed between IC and minCOM using MATLAB (MathWorks, Natick, MA, USA). Temporal data were interpolated to 101 data points (100% of cycle) for the SPM analysis.

STATISTICAL PARAMETRIC MAPPING

All SPM analyses were conducted in MATLAB using an open-source software package spm1D 0.4.[27] Multiple paired *t*-tests ($p < 0.05$) were performed with Bonferroni corrections to compare the grouped kinematic data of lower extremity limbs for all participants at each percentage of the cycle. For group analysis the mean trajectories of each participant's twenty trials (10 on each leg) were used. Additionally, paired *t*-tests were performed comparing the limbs for each individual participant that was calculated using 10 trials from each limb. The significance level for all statistical tests after the alpha corrections was ($p = 0.006$). The null hypothesis was rejected if the computed *t*-value exceeded the critical threshold. In SPM the *t*-value is calculated across the temporal region of interest (i.e., IC to minCOM). Whereas, the critical threshold is a product of random field theory that can be used to determine a threshold where equivalently smooth Gaussian random fields would cross at the specified alpha level when the null hypothesis is true.[28]

RESULTS

The group SPM analysis with paired *t*-tests did not reveal any significant differences between the dominant and non-dominant limbs for all kinematic variables (Figure 2).

Individual SPM analysis with paired *t*-tests revealed significant kinematic differences between the right and left limbs for all participants. At the hip in the sagittal plane, seven participants had a significant difference between their two limbs. During the phase when the difference between lower limbs exceeded the critical threshold, four of those seven participants had a relative increase in hip flexion on the right limb (Figure 3).

Conversely, the remaining three with significant differences were shown to have increased hip flexion on their left limb. At the knee in the sagittal plane, seven participants had a significant relative difference between their two limbs (Figure 4).

Four of those participants increased knee flexion on the left limb and three increased knee flexion on the right limb. Anterior pelvic tilt was greater when landing on the left limb in five participants, and in three participants when landing on their right limb (Figure 5).

For frontal plane hip motion, six participants had increased hip adduction on the right limb and three participants had relatively increased adduction on the left limb (Figure 6).

At the knee, two participants had increased knee abduction on the right limb, 4 had relative increases on the left limb, and participants six and eight had relative differences between limbs in both directions (Figure 7).

Significant differences for pelvic drop occurred in eight of the nine participants (Figure 8).

Six of those participants had a relative decrease in pelvic drop when landing on their right limb.

DISCUSSION

The aim of this study was to examine physically active females for potential bilateral differences in pelvis, hip, and knee kinematics during a SLD task. A group analysis (comparison of mean data between right and left limbs) and a single subject design was used to ascertain the findings of potential bilateral differences among the population studied. The findings indicated that there were no significant differences for kinematic variables between the right and left limbs when analyzed at a group level. However, this was not indicative that bilateral differences were not prevalent among the study's population. For instance, each of

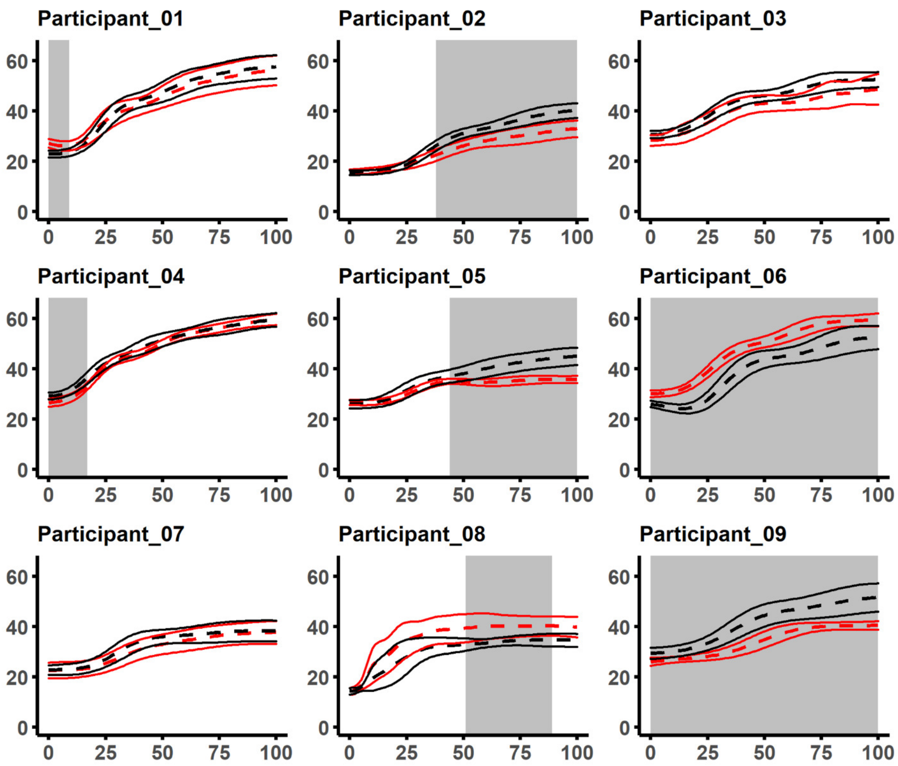

Figure 3. Hip sagittal plane kinematics for each participant from initial contact to the minimum height of the center of mass.

Positive values indicate hip flexion. Mean values are represented by dashed lines with the solid lines indicating standard deviations. The right limb is shown as black, and the left shown as red. Shaded areas represent significant differences as determined from the statistical parametric mapping.

the participants demonstrated at least two asymmetries out of the six variables in question and six out of the nine participants had bilateral differences for all kinematic time-series. Thus, the hypothesis that bilateral differences would be observed at the single subject design level, but not at the group level was accepted. The consequence of group analysis concealing individual differences is not novel to the current study.[29–31]

The data were grouped by right and left limbs because there is currently not a clear metric for determining limb dominance during a SLD task. However, the selection of comparing right and left limbs was not an adequate method for homogenizing participant data to describe the observed differences between limbs. Therefore, the approach of including a single subject design allowed us to look at bilateral differences without defining the criteria of which leg was dominant during the task. It should be noted that all participants reported that they preferred kicking a ball with their right limb. Thus, grouping limbs by this metric would not have affected the outcome of the data.

The absence of significant group findings may be explained by not all participants displaying similar movement patterns with their right or left limb. For example, participants (4, 5, 9) had a significant relative increase for hip flexion angles on their right limbs when compared to their left (Figure 3). Conversely, participants (1, 2, 6, 8) demonstrated greater hip flexion on their left limb (Figure 3). Similar participant variability was also observed in the other variables of interest. Thus, it appears that in this sample population of uninjured participants, the heterogeneous movement patterns influenced the findings at a group level and provided support for the use of single subject analysis.

The current study's group findings in recreational female athletes are similar with those of Wang and Fu[21] who found no bilateral differences in female soccer players at IC. However, the researchers[15] did not include a single subject design which may have limited their interpretation of their results. For instance, when considering this study, four of the participants (1, 4, 6, 9) had a significant difference for hip and knee flexion at IC (Figure 3, 4). Interestingly, for hip frontal plane motion all but one of the participants (8) demonstrated a significant difference at IC (Figure 6). At the knee in the frontal plane, all but two of the participants (4, 8) had statistically similar waveforms at IC (Figure 7). Another difference between the two studies methods is the fact that the female soccer players dropped from a box 20cm shorter than what was used for the current study's participants (60cm).

It has been shown that increasing the height of the SLD task may result in greater bilateral kinematic differences.[16] In a study where participants landed from the same height for the SLD task as the current study, the researchers[16] also reported that no bilateral differences were observed for hip and knee flexion between the limbs of recreationally active females. However, the researchers[16] analyzed the kinematic data at the moment of peak vertical GRF because it was thought to be related to the timing of injury. As discrete time points were not considered in the current analy-

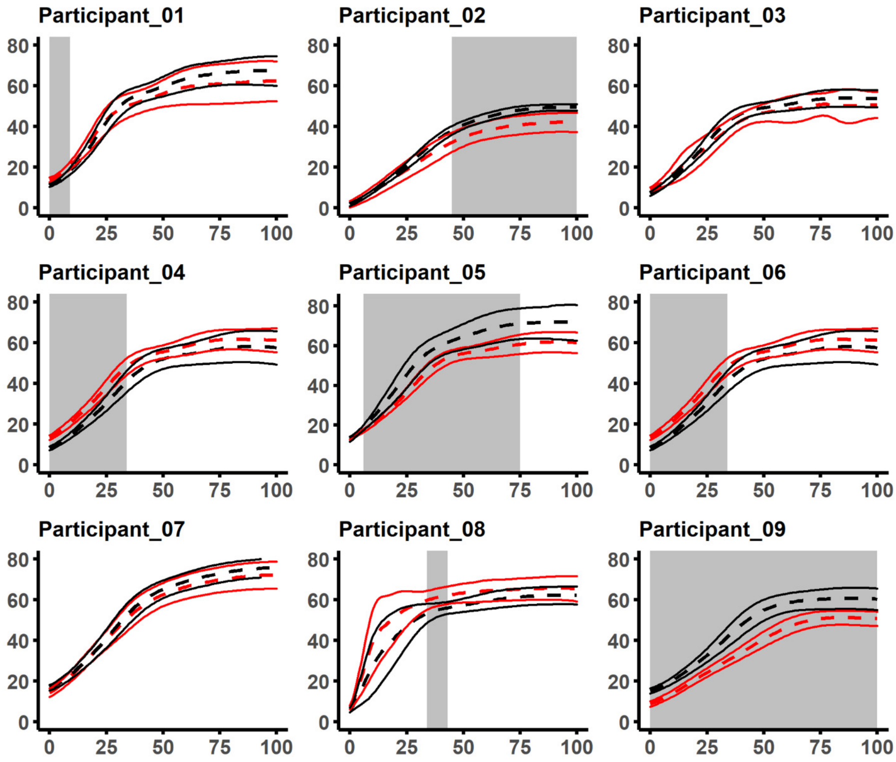

Figure 4. Knee sagittal plane kinematics for each participant from initial contact to the minimum height of the center of mass.

Positive values indicate knee flexion. Mean values are represented by dashed lines with the solid lines indicating standard deviations. The right limb is shown as black, and the left shown as red. Shaded areas represent significant differences as determined from the statistical parametric mapping.

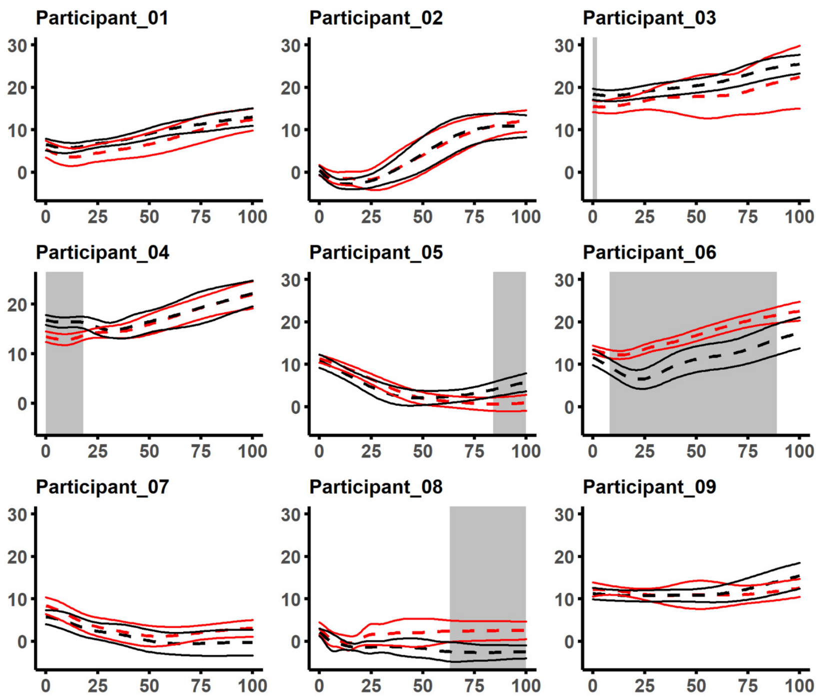

Figure 5. Pelvis sagittal plane kinematics for each participant from initial contact to the minimum height of the center of mass.

Positive values indicate anterior pelvic tilt. Mean values are represented by dashed lines with the solid lines indicating standard deviations. The right limb is shown as black, and the left shown as red. Shaded areas represent significant differences as determined from the statistical parametric mapping.

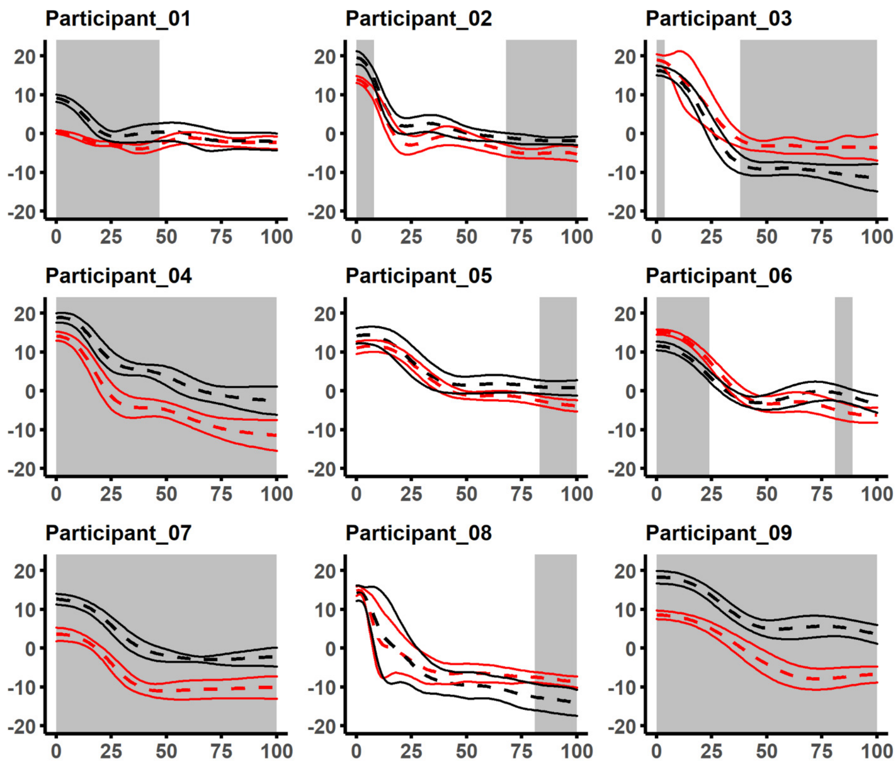

Figure 6. Hip frontal plane kinematics for each participant from initial contact to the minimum height of the center of mass.

Positive values indicate hip adduction. Mean values are represented by dashed lines with the solid lines indicating standard deviations. The right limb is shown as black, and the left shown as red. Shaded areas represent significant differences as determined from the statistical parametric mapping.

sis (other than to determine the beginning and end of the movement) it is difficult to draw comparisons with their kinematic data. The discrepancies between cadaveric[7,32] and model simulated ACL strain[11,12] is conflicting for researchers looking to identify the optimal time or joint angle for assessing risky lower extremity movement patterns. Research from cadaveric modeling has been used to suggest that peak ACL strain occurs simultaneously with peak knee abduction angles.[33,34] Thus, there is a potential advantage of using a wave form analysis technique as it limits the bias of researchers when selecting discrete time points for analysis.

To the best of the authors' knowledge, this is the first study to include pelvic kinematics with bilateral comparison during a SLD task in females. Bilateral pelvic imbalances may be relevant to injury prevention as increased pelvic kinematics have been shown to result in amplified torque at the knee in the frontal plane during a SLD jump.[35] Only three of the participants (Figure 8) displayed mean pelvic drop angles below 0° (neutral). However, these findings may be more indicative of the SLD methods than the ability of the participants to stabilize their pelvis in the frontal plane. For example, each of the participants landed with a negative pelvic drop (i.e., their hip on their landing limb was lower). This is likely due to asking them to step off the box with the same limb that they landed on. If the participants had landed in a more neutral position, greater pelvic drop angles may have been observed. Nonetheless, all but one of the participants (8) demonstrated a bilateral difference. Interestingly, six of the participants (1, 2, 3, 5, 7, 9) who landed in a more neutral pelvic position (closer to 0°) had increased knee abduction angles on the same limb (Figure 7, 8). This suggests that pelvic and knee kinematics may be linked during a SLD task. However, a causative relationship cannot be established with the current evidence.

When examining anterior pelvic tilt, most of the participants (3-9) demonstrated a significant bilateral difference. Although the purpose of the current study was not to describe the ideal anterior pelvic tilt during the movement task, it may be that not all participants with bilateral differences possess inadequate pelvic control. For instance, participants 7, 8, and 9 either maintained a relatively neutral pelvis, or decreased the amount of pelvic tilt throughout the motion (Figure 5). In contrast, participants 1 and 2 did not present with bilateral differences but increased their degree of anterior pelvic tilt from initial contact to the end of the movement.

Although the results of this single subject analysis indicated that each of the participants had kinematic imbalances during the SLD task, it is still unclear whether these asymmetries were suggestive of poor movement patterns (on one or both limbs) that may facilitate an increased risk of injury. It may be that the observed bilateral differences were simply a result of performance variability between the two limbs. In short, performance variability is a natural biologic phenomenon that adapts for desired outcomes based on force distribution mechanisms, development or skill level, and environmental factors.[23] Inter-indi-

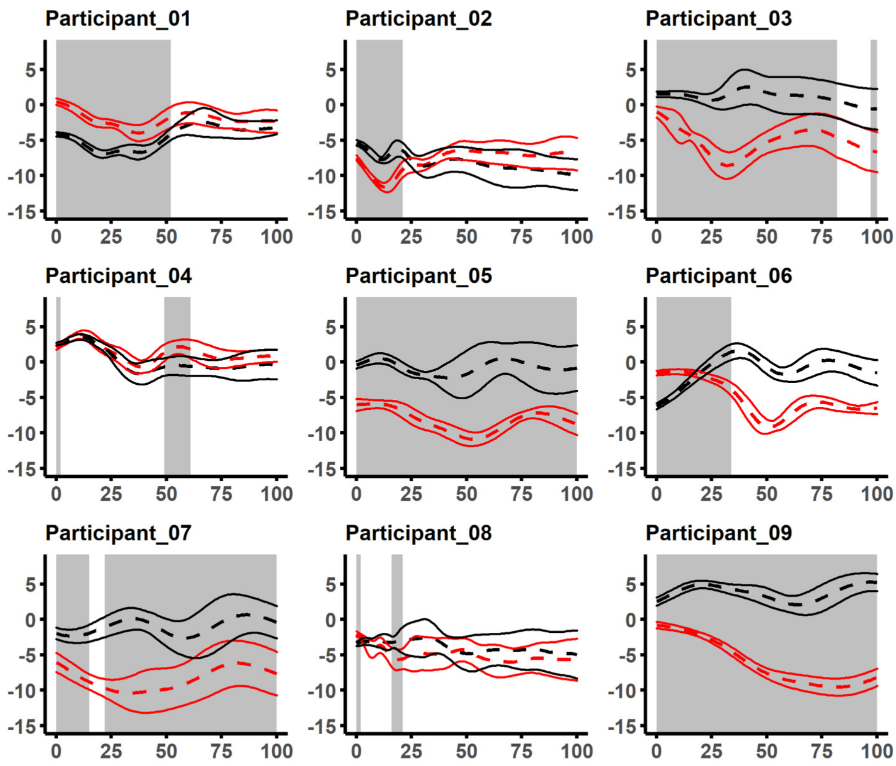

Figure 7. Knee frontal plane kinematics for each participant from initial contact to the minimum height of the center of mass.

Positive values indicate knee abduction. Mean values are represented by dashed lines with the solid lines indicating standard deviations. The right limb is shown as black, and the left shown as red. Shaded areas represent significant differences as determined from the statistical parametric mapping.

vidual variability has been shown to occur in professional athletes during basketball shooting and elite javelin throwers,[30] as well as in recreational athletes while running and performing a SLD.[23,30] The participants' bilateral kinematic differences in the current study may have been compensations that occurred due to muscular strength imbalances, prior training, or possibly structural/anatomical asymmetries. Thus, the observed imbalances may have been necessary to complete the task. Further research is needed to examine the circumstances in which movement compensations and bilateral differences are beneficial or detrimental.

This study has several limitations. First, the current study only collected data on a small sample of physically active female participants. Group findings may have been apparent if participants had more homogeneous training backgrounds. A larger sample size may also have provided a greater probability of observing differences at the group level. Second, participants were only stratified based on their right or left limb. Future research might examine the potential for task specific methods to dichotomize limbs. For example, participants may self-identify their preferred landing limb. Lastly, due to the method participants dropped off the box (i.e., stepping), there may have been differences in the distance they fell onto the force plate, either between legs, or participants.

CONCLUSION

At the single subject analysis level, participants were asymmetrical regarding their kinematic time-series. However, these differences were not observed in any of the waveforms for the group analysis. The authors recommend that until an accepted method for dichotomizing right and left limbs for bilateral comparisons is accepted, single subject design should be included with any group analysis where bilateral differences are examined.

DISCLOSURES

This study was approved by the University of Idaho Institutional Review Board, irb@uidaho.edu

The authors did not have any financial or personal relationships with people or organizations that may have inappropriately influenced or biased their work.

Submitted: May 11, 2022 CST, Accepted: September 12, 2022 CST

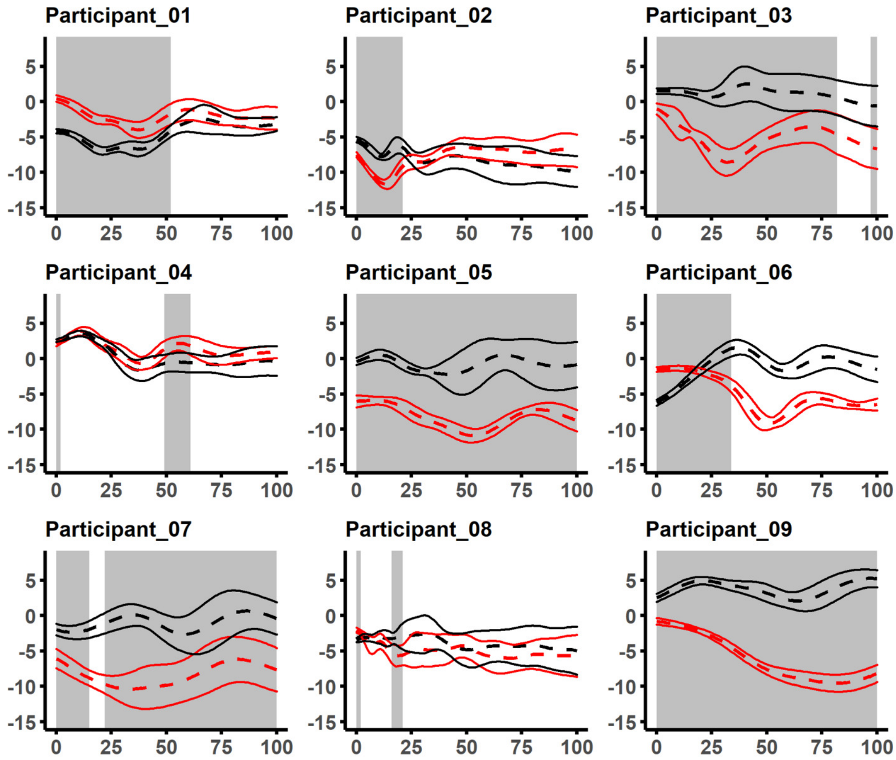

Figure 8. Pelvic frontal plane kinematics for each participant from initial contact to the minimum height of the center of mass.

Positive values indicate pelvic drop. Mean values are represented by dashed lines with the solid lines indicating standard deviations. The right limb is shown as black, and the left shown as red. Shaded areas represent significant differences as determined from the statistical parametric mapping.

REFERENCES

1. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk: A prospective biomechanical-epidemiologic study. *Am J Sports Med*. 2007;35(7):1123-1130. doi:10.1177/0363546507301585

2. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes A prospective study. *Am J Sports Med*. 2005;33(4):492-501. doi:10.1177/0363546504269591

3. Arendt EA, Agel J, Dick R. Anterior cruciate ligament injury patterns among collegiate men and women. *J Athl Train*. 1999;34(2):86-92.

4. Ruedl G, Webhofer M, Helle K, et al. Leg dominance is a risk factor for noncontact anterior cruciate ligament injuries in female recreational skiers. *Am J Sports Med*. 2012;40(6):1269-1273. doi:10.1177/0363546512439027

5. Brophy R, Silvers HJ, Gonzales T, Mandelbaum BR. Gender influences: the role of leg dominance in ACL injury among soccer players. *Br J Sports Med*. 2010;44(10):694-697. doi:10.1136/bjsm.2008.051243

6. Greska EK, Cortes N, Ringleb SI, Onate JA, Van Lunen BL. Biomechanical differences related to leg dominance were not found during a cutting task. *Scand J Med Sci Sports*. 2016;27(11):1328-1336. doi:10.1111/sms.12776

7. Kiapour AM, Demetropoulos CK, Kiapour A, et al. Strain response of the anterior cruciate ligament to uniplanar and multiplanar loads during simulated landings. *Am J Sports Med*. 2016;44(8):2087-2096. doi:10.1177/0363546516640499

8. Koga H, Nakamae A, Shima Y, et al. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. *Am J Sports Med*. 2010;38(11):2218-2225. doi:10.1177/0363546510373570

9. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *Am J Sports Med*. 2005;33(4):492-501. doi:10.1177/0363546504269591

10. Boden BP, Sheehan FT, Torg JS, Hewett TE. Non-contact ACL injuries: mechanisms and risk factors. *J Am Acad Orthop Surg*. 2010;18(9):520-527. doi:10.5435/00124635-201009000-00003

11. Utturkar GM, Irribarra LA, Taylor KA, et al. The effects of a valgus collapse knee position on in vivo ACL elongation. *Ann Biomed Eng*. 2013;41(1):123-130. doi:10.1007/s10439-012-0629-x

12. Englander ZA, Baldwin EL III, Smith WAR, Garrett WE, Spritzer CE, DeFrate LE. In vivo anterior cruciate ligament deformation during a single-legged jump measured by magnetic resonance imaging and high-speed biplanar radiography. *Am J Sports Med*. 2019;47(13):3166-3172. doi:10.1177/0363546519876074

13. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc*. 2003;35(10):1745-1750. doi:10.1249/01.mss.0000089346.85744.d9

14. Pappas E, Carpes FP. Lower extremity kinematic asymmetry in male and female athletes performing jump-landing tasks. *J Sci Med Sport*. 2012;15(1):87-92. doi:10.1016/j.jsams.2011.07.008

15. Wang J, Fu W. Asymmetry between the dominant and non-dominant legs in the lower limb biomechanics during single-leg landings in females. *Adv Mech Eng*. 2019;11(5):1-8. doi:10.1177/1687814019849794

16. Mokhtarzadeh H, Ewing K, Janssen I, Yeow CH, Brown N, Lee PVS. The effect of leg dominance and landing height on ACL loading among female athletes. *J Biomech*. 2017;60:181-187. doi:10.1016/j.jbiomech.2017.06.033

17. van der Harst JJ, Gokeler A, Hof AL. Leg kinematics and kinetics in landing from a single-leg hop for distance. A comparison between dominant and non-dominant leg. *J Clin Biomech*. 2007;22(6):674-680. doi:10.1016/j.clinbiomech.2007.02.007

18. Whyte EF, Richter C, O'Connor S, Moran KA. Investigation of the effects of high-intensity, intermittent exercise and unanticipation on trunk and lower limb biomechanics during a side-cutting maneuver using statistical parametric mapping. *J Strength Cond Res*. 2018;32(6):1583-1593. doi:10.1519/jsc.0000000000002567

19. Sugiyama T, Kameda M, Kageyama M, Kiba K, Kanehisa H. Asymmetry between the dominant and non-dominant legs in the kinematics of the lower extremities during a running single leg jump in collegiate basketball players. *J Sport Sci Med*. 2014;13:951-957.

20. Brown TN, Palmieri-Smith RM, Mclean SG. Sex and limb differences in hip and knee kinematics and kinetics during anticipated and unanticipated jump landings: implications for anterior cruciate ligament injury. *Br J Sport Med*. 2009;43(13):1049-1056. doi:10.1136/bjsm.2008.055954

21. Wang J, Fu W. Asymmetry between the dominant and non-dominant legs in the lower limb biomechanics during single-leg landings in females. *Adv Mech Engin*. 2019;11(5):168781401984979. doi:10.1177/1687814019849794

22. Mcgrath TM, Waddington G, Scarvell JM, et al. The effect of limb dominance on lower limb functional performance – a systematic review. *J Sport Sci*. 2015;34(4):289-302. doi:10.1080/02640414.2015.1050601

23. Schot PK, Bates BT, Dufek JS. Bilateral performance symmetry during drop landing: a kinetic analysis. *Med Sci Sport Exerc*. 1994;26(9):1153-1159. doi:10.1249/00005768-199409000-00013

24. Richter C, O'Connor NE, Marshall B, Moran K. Comparison of discrete-point vs. dimensionality-reduction techniques for describing performance-related aspects of maximal vertical jumping. *J Biomech*. 2014;47(12):3012-3017. doi:10.1016/j.jbiomech.2014.07.001

25. Pataky TC. Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *J Biomech*. 2010;43(10):1976-1982. doi:10.1016/j.jbiomech.2010.03.008

26. Ithurburn MP, Paterno MV, Ford KR, Hewett TE, Schmitt LC. Young athletes with quadriceps femoris strength asymmetry at return to sport after anterior cruciate ligament reconstruction demonstrate asymmetric single-leg drop-landing mechanics. *Am J Sports Med*. 2015;43(11):2727-2737. doi:10.1177/0363546515602016

27. Pataky TC. One-dimensional statistical parametric mapping in Python. *Comput Methods Biomech Biomed Engin*. 2012;15(3):295-301. doi:10.1080/10255842.2010.527837

28. Pataky TC. rft1d: Smooth one-dimensional random field upcrossing probabilities in python. *J Stat Soft*. 2016;71(7). doi:10.18637/jss.v071.i07

29. Scholes CJ, Mcdonald MD, Parker AW. Single-subject analysis reveals variation in knee mechanics during step landing. *J Biomech*. 2012;45(12):2074-2078. doi:10.1016/j.jbiomech.2012.05.046

30. Bartlett R, Wheat J, Robins M. Is movement variability important for sports biomechanists? *Sport Biomech*. 2007;6(2):224-243. doi:10.1080/14763140701322994

31. Õunpuu S, Winter DA. Bilateral electromyographical analysis of the lower limbs during walking in normal adults. *Electro Clin Neurophysiol*. 1989;72(5):429-438. doi:10.1016/0013-4694(89)90048-5

32. Kiapour AM, Quatman CE, Goel VK, Wordeman SC, Hewett TE, Demetropoulos CK. Timing sequence of multi-planar knee kinematics revealed by physiologic cadaveric simulation of landing: Implications for ACL injury mechanism. *Clin Biomech*. 2014;29(1):75-82. doi:10.1016/j.clinbiomech.2013.10.017

33. Kiapour AM, Demetropoulos CK, Kiapour A, et al. Response of the anterior cruciate ligament to uniplanar and multiplanar loads during simulated landings: implications for injury mechanism. *Am J Sports Med*. 2016;44(8):2087-2096. doi:10.1177/0363546516640499

34. Kiapour AM, Quatman CE, Goel VK, Wordeman SC, Hewett TE, Demetropoulos CK. Timing sequence of multi-planar knee kinematics revealed by physiologic cadaveric simulation of landing: Implications for ACL injury mechanism. *J Clin Biomech*. 2014;29(1):75-82. doi:10.1016/j.clinbiomech.2013.10.017

35. Chijimatsu M, Ishida T, Yamanaka M, et al. Landing instructions focused on pelvic and trunk lateral tilt decrease the knee abduction moment during a single-leg drop vertical jump. *Phys Ther Sport*. 2020;46:226-233. doi:10.1016/j.ptsp.2020.09.010