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Examining movement asymmetries during three single leg tasks using interlimb and single subject approaches

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ABSTRACT

Purpose: s: To examine whether healthy individuals displayed asymmetric trunk and lower extremity kinematics in the frontal and sagittal planes using both interlimb and single subject models.
Methods: Trunk, pelvis, and lower extremity kinematic waveforms were analyzed bilaterally during the single leg squat (SLS), forward step down (FSD), and lateral step down (LSD). Participants identified task specific preferred and non-preferred legs based on perceived stability for interlimb analyses. Movement patterns were also analyzed with a single subject approach that included Fisher's exact tests to assess whether asymmetries were related to the task.
Results: Participants were found to have increased pelvic drop on the non-preferred leg during the LSD from 41 to 77% of the movement ($p = 0.01$). No other bilateral differences were found for interlimb analyses. Single subject analyses indicated that no task had a greater probability of finding or not finding asymmetries. Associations were found between the FSD and SLS for frontal plane hip ($p < 0.01$) and knee motion ($p < 0.01$).
Conclusions: Interlimb analyses can be influenced by intraparticipant movement variability between preferred and non-preferred legs. Movement asymmetries during single leg weightbearing are likely task dependent and a battery of tests is necessary for assessing bilateral differences.

1. Introduction

Investigations of movement symmetry often focus on differences in the mean data of multiple participants (i.e., interlimb differences), without consideration for single subject analyses (Greska, Cortes, Ringleb, Onate, & van Lunen, 2017; Ksoll et al., 2022; Mokhtarzadeh et al., 2017). Although inferential data from a collection of individual movement patterns may provide information on the probability that the average performance within the study's sample will occur in a larger population, different individual movement strategies within the sample can affect the statistical outcomes (Dufek, Bates, Stergiou, & James, 1995). The effect of different movement strategies may be of particular importance when determining the potential for bilateral asymmetries (Flanagan & Salem, 2007; Schot, Bates, & Dufek, 1994). For example, interlimb asymmetries would not be apparent in a situation where half of the population had statistically increased values on the "dominant" side and the other half had greater values on the "non-dominant" side: interlimb data in this situation would indicate a lack of statistically significant differences between sides despite all participants having a difference between legs. Including a single subject post hoc analyses in addition to inferences made from interlimb comparisons provides an extra level of analysis that is not influenced by limb classification (Dufek et al., 1995; Flanagan & Salem, 2007; Martonick, Chun, Krumpl, & Bailey, 2022). Additionally, a method that dichotomized legs so that participants performed similarly on their classified legs (e.g., greater knee valgus on the non-preferred leg) may enable findings of asymmetry that would otherwise not be observed due to individual movement strategies.

Selection of the appropriate leg for dichotomization is a challenge when investigating the potential of bilateral differences to occur when assessing mean data calculated from multiple individuals. This difficulty is attributed to the fact that individuals will often develop a tendency to perform movement patterns with an approach that favors one side of the body. The term "lateral preference" (often termed leg dominance) has

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been used to describe the development of a specific arm or leg to perform a given task (Carpes, Mota, & Faria, 2010; McGrath et al., 2016). A common method for determining leg dominance is to identify the leg used to kick a ball (Greska et al., 2017); however, lateral preference has been found to be task specific (Carcia, Cacolice, & McGeary, 2019; van Melick, Meddeler, Hoogeboom, Nijhuis -; van der Sanden, & van Cingel, 2017; Velotta, Weyer, Ramirez, Winstead, & Bahamonde, 2011). For instance, the preferred kicking leg and preferred landing leg have been found to have no association in both athletes (Cacolice, Starkey, Carcia, & Higgins, 2022) and non-athletes (Carcia et al., 2019) alike. Likewise, investigations of asymmetries in lower extremity force production have found that participants rarely favor the same leg across a variety of single and double leg vertical jumping tasks (Bishop et al., 2020; Loturco et al., 2018). This information indicates that lateral preferences should be assessed on a task-by-task basis and multiple tasks may be necessary to show the "full picture" when analyzing movement asymmetries (Bishop et al., 2020; Loturco et al., 2018).

Movement tasks such as the single leg squat (SLS), forward step down (FSD) and lateral step down (LSD) are clinically applicable tools for tracking unilateral movement (Rabin & Kozol, 2010; Ressman, Grooten, & Rasmussen, 2019). Although the kinematic profiles of the FSD, SLS, and LSD have been compared with healthy individuals (Lewis, Foch, Luko, Loverro, & Khuu, 2015; Lopes Ferreira et al., 2019; Martonick, McGowan, Larkins, Baker, & Bailey, 2022; Werner et al., 2021), these investigations have only examined differences between the tasks using one side of the body. Current evidence is limited regarding whether bilateral symmetry of healthy individuals should be assumed when performing one or all of these tasks. Insights for the potential of healthy individuals to have asymmetric movement patterns that are task specific could improve clinical decision making when assessing and resolving movement asymmetries in clinical settings. To fully elucidate the potential of asymmetry to occur and the effect of task on symmetry, the purpose of this study was three-fold: (1) examine whether healthy individuals displayed asymmetric trunk and lower extremity kinematics in the frontal and sagittal planes using both interlimb and single subject models, (2) determine whether specific tasks were more associated with kinematic asymmetries, and (3) evaluate whether asymmetries were task specific.

2. Methods

2.1. Participants

A convenience sample of twenty-three participants were recruited from the local university including 11 females and 12 males (mean age 21.4 ± 1.7 and 24.7 ± 3.3 years old; mean height 174.2 ± 6.7 cm and 181.4 ± 6.4 cm; and mean body mass 62.3 ± 9.9 kg and 82.8 ± 7.8 kg) volunteered for this within-subjects, repeated-measures study design. Only 21 participants of which 11 were female were used in the LSD analyses, gaps in the marker trajectories of two participants which lead to an inadequate number of trials. To be included, participants had to be able to perform the SLS to 60°of knee flexion while maintaining their hands on their waist as signs of both mobility and stability. The ability to perform the SLS to 60° of knee flexion is considered to be the minimum depth for a squat to be clinically rated as "good" (Khuu, Foch, & Lewis, 2016). Participants who reported a current lower extremity injury, pain during any of the tasks, or prior history of lower extremity or low back surgery were excluded. All participants were informed of the risks of participation and signed an informed consent form approved by the University's Institutional Review Board prior to participation.

2.2. Procedures

Prior to collecting data, participants were familiarized with each task (FSD, SLS, LSD) while a member of the research instructed them on how to perform each task. Instructions included positioning of the non-weightbearing leg, where to stand on the box, and hand positioning, but did not include cueing them on form (i.e., pelvic drop, knee valgus). For the SLS participants were instructed to squat to a depth that they could come out of without pausing at the bottom. During the familiarization period, participants were allowed to perform each task bilaterally until they felt comfortable enough to determine which leg they identified as the most stable for each task. The self-identified 'most stable' leg was used as their preferred leg for that individual task. Lateral preference (i.e., limb dominance) for this study was task specific creating the possibility of differences across tasks per participant (Carpes et al., 2010; McGrath et al., 2016). Participants were then fitted with a custom cluster-based on 42 reflective markers that defined the trunk, pelvis, thighs, and shanks based on marker placement of a previous study (Lewis et al., 2015). Calibration markers at the knee and pelvis were applied by a single investigator to maintain a consistency of measurement (Pohl, Lloyd, & Ferber, 2010). Calibration markers were removed after a standing static calibration trial used to create a subject-specific model. Trials were collected with an 8-camera motion capture system (Vantage, 250Hz, Vicon Motion Systems Ltd., Oxford, UK). Following instrumentation, participants were asked to perform each task bilaterally, collecting 5 'good trials' per side. A trial was rated as 'not good' and recollected if the participant's hands came off their waist, the trial was performed in a non-continuous manner (i.e., pausing at the bottom, reaching twice to touch the floor with their heel), or balance was lost. Participants completed all trials of one task prior to changing tasks. Task order was randomized across participants to account for order effect. Limb order was randomized for the first task, and subsequent tasks were performed in a sequence so that the participants did not perform back-to-back tasks on the same leg. The non-weightbearing leg was placed in a neutral hip position by having the participant stand upright on both legs and then flexing non-weightbearing knee to approximately 90° so that the knee was pointed down. The hip was maintained in this position for the duration of the task. Both step down tasks (FSD and LSD) were performed with the participant standing toward the edge of a 20 cm box. For the FSD, participants stood with the toes of their stance leg at the edge of the box and dorsiflexed their non-weightbearing foot. They were instructed to lightly touch their heel to the ground, then return to their starting position in one continuous motion (Lopes Ferreira et al., 2019; Park, Cynn, & Choung, 2013). The same procedure was followed for the LSD; however, the medial aspect of the weight-bearing foot was placed parallel to the edge of the box (Lopes Ferreira et al., 2019).

2.3. Data analysis

Angular kinematics were computed using a Cardan (X-Y-Z) rotation sequence with Visual 3D software (v6, C-Motion Inc., Germantown, MD, USA). The pelvis was modeled as a CODA pelvis, with segment angles calculated relative to the global coordinate system. Pelvis segmental 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 (Baker, 2001). Pelvic drop was defined with respect to the frontal plane, whereas pelvic tilt was defined with respect to the sagittal plane. Positive values in the frontal plane were represented as a contralateral pelvic drop and positive values in the anterior plane represented anterior pelvic tilt. Ipsilateral trunk lean was defined as a positive value and indicated frontal plane motion toward the weight bearing leg. Trunk, hip, and knee flexion were defined as positive values in the sagittal plane. Hip adduction and knee abduction (valgus) were represented as positive values in the frontal plane.

Marker trajectories were low-pass filtered using a fourth-order Butterworth filter at 6 Hz (Khuu et al., 2016; Lewis et al., 2015). Kinematic time-series were interpolated to 101 data points (100% of cycle) for the Statistical Parametric Mapping (SPM) analysis from the beginning to the end of the task using a custom MATLAB script (MathWorks, Natick, MA, USA). During the first second of each task, participants were asked to hold their position for a quiet stance period. During this period, the standard deviation of hip flexion for the stance limb was calculated. The beginning of the task was identified when hip flexion of the stance limb exceeded a change at least 3 standard deviations from the quiet stance period (Lake & McMahon, 2018). The end of the task was defined as the point when hip flexion returned to that starting value.

2.4. Statistical analysis

All SPM analyses were conducted in MATLAB using an open-source software package spm1D 0.4 (Pataky, 2012). Paired *t*-tests were performed between preferred and non-preferred legs for the interlimb analysis (i.e., preferred vs. non-preferred). To assess interlimb data, the participant's mean kinematic waveforms of the five trials, for both the preferred and non-preferred legs, were calculated for each task and used for analysis. The significance level for all SPM tests was set a priori to an alpha of 0.05. A Bonferonni correction was not deemed appropriate because the procedure requires independence across the tests which may not be the case with time-series data (Houston, Fong, Bennett, Walters, & Barker-Davies, 2021). Additionally, SPM analyses have been found to reduce type I error associated with kinematic data (Houston et al., 2021; Pataky, 2016). The null hypothesis was rejected if the computed *t*-value exceeded the critical threshold.

For the single subject analyses, the five trials were compared between the two legs for each task (Bates, Dufek, & Davis, 1992). When the participant's statistical difference between legs crossed the critical threshold, the timing of this cross from 0 to 100% of the movement was recorded. If any portion of the task reached statistical difference, the participant was classified as having an asymmetry for that variable and task. The single subjects data were assessed with Fisher's exact tests to determine whether symmetries or asymmetries occurred more often when performing a given task (Fig. 1), as well as whether symmetries or asymmetries were associated between two tasks (Fig. 2). Fisher's exact tests were selected to account for contingency table cells with a value less than 5 (Nowacki, 2017). Additionally, the Fisher's exact tests provided odds ratios (OR) and their confidence intervals (CI) to determine the direction of the relationship (Szumilas, 2010). Tasks were considered to have a relationship when the null hypothesis was rejected ($p < 0.05$), and the odds ratio was greater than or less than one with the confidence interval not including a value of one (Szumilas, 2010). Fisher's exact tests were also used to assess whether there were any relationships between tasks for the self-identified most stable leg. Contingency tables were created and assessed with the R software package *stats* (version 4.1.2; The R Foundation for Statistical Computing Platform, 2021).

3. Results

Contralateral pelvic drop was increased on the non-preferred leg

Task	Asymmetry		
	Yes	No	Task Σ
LSD	14	7	21
SLS	12	11	23

Fig. 1. Contingency table example assessing whether participants had a greater probability of pelvic drop asymmetries for either the Lateral Step Down (LSD), or Single Leg Squat (SLS).

SLS Asymmetry	FSD Asymmetry		
	Yes	No	SLS Σ
Yes	15	3	18
No	1	4	5
FSD Σ	16	7	N = 23

Fig. 2. Contingency table example assessing whether there was a relationship between the Single Leg Squat (SLS) and Forward Step Down (FSD) for participants with asymmetries for knee abduction. Cells fully shaded in gray show agreement between tasks, and cells shaded in half indicate participants with asymmetries for one or neither task.

from 41 to 77% of the movement ($p = 0.01$, Fig. 3) for the LSD interlimb analysis. No other statistically significant differences were found for the LSD interlimb analysis or for bilateral differences recorded during the FSD and SLS throughout the entire cycle for the interlimb analyses. For the single subject analyses, the number of participants with significant differences were task and variable dependent. Results of the Fisher's exact tests did not include any significant relationships that would indicate one task had a greater probability of participants having an asymmetry or not for any given variable (Table 1). Examination of the probability that participants would have or not have asymmetries in two different tasks revealed a significant relationship between the FSD and SLS for pelvic drop ($p = 0.01$, OR = 11.52 (1.34–172.78)), and knee abduction ($p = 0.01$, OR = 16.56 (1.16–1038.60)) (Table 2). Participants were found to have an association between the LSD and FSD for the selection of their preferred limb ($p < 0.01$, OR = 22.90 (1.91–1348.01)), however; selection of the preferred limb for the SLS did not have a relationship with the other two tasks (LSD:SLS, $p = 0.10$, OR = 4.62 (0.61–44.89); FSD:SLS, $p = 0.18$, OR = 4.25 (0.53–42.32)).

4. Discussion

The primary purpose of this study was to examine whether healthy individuals displayed asymmetric trunk and lower extremity kinematics in the frontal and sagittal planes using both interlimb and single subject models. Across the three tasks, interlimb analyses found only one asymmetry between the preferred and non-preferred legs, and this was for frontal plane motion of the pelvis during the LSD. However, the single subject analyses demonstrated that movement asymmetries could be prevalent for a given variable although interlimb analyses found no difference. For example, no interlimb differences were found across tasks for frontal plane knee motion although 71% of participants had bilateral differences during the LSD, 70% during the FSD, and 78% during the SLS (Fig. 4). The large percentage of individual asymmetries at the knee in the frontal plane and the lack of bilateral differences for the interlimb analyses indicates that discrepancies may exist between the two models.

The potential incongruities between models may be explained by dissimilar movement patterns for the participant identified preferred and non-preferred legs. Specifically, differences for interlimb means may have been canceled out by some participants having greater magnitudes on the preferred leg and others on the non-preferred leg. For instance, of the 70% of participants with bilateral differences during the FSD, half perceived they were more stable on the leg with increased frontal plane knee motion. Additionally, the only interlimb difference

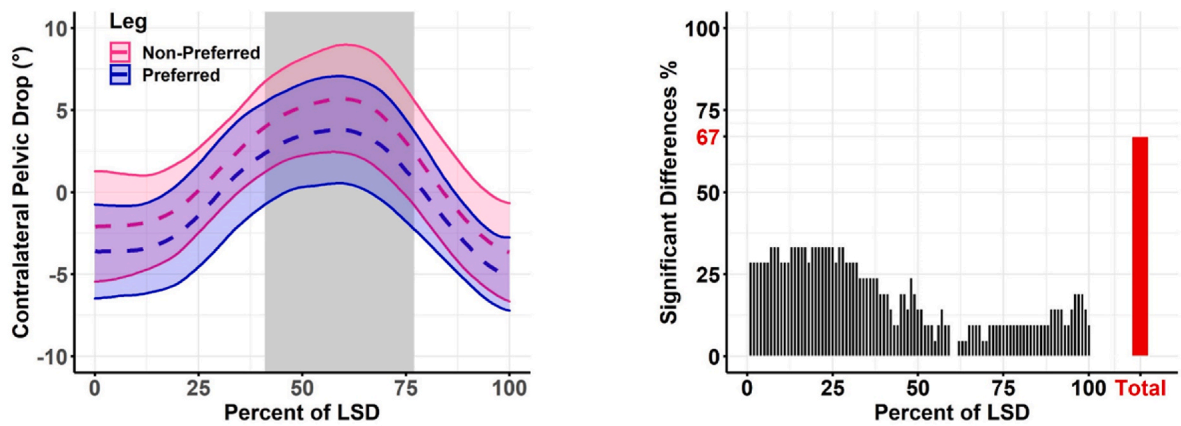

Fig. 3. Left plot displays time series for interlimb comparisons of pelvic drop during the Lateral Step Down (LSD). Shaded gray region indicates time of significant difference. Right plot displays results of single subjects analyses. Black bars represent the percentage of participants with a significant difference at each percentage of the task. The red bar indicates the total percentage of individuals with a significant difference. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Results of Fisher's exact tests for the association task for the presence of asymmetry. Odds ratios and confidence intervals (CI) imply the direction of the association (LSD vs. FSD: odds ratio >1 = FSD has greater odds of asymmetry, LSD vs. SLS: odds ratio <1 = SLS has greater odds of asymmetry, FSD vs SLS: odds ratio <1 = SLS has greater odds of asymmetry).

Tasks	Variable	p-value	odds ratio	CI
LSD vs FSD	Trunk Flexion	0.53	0.63	0.14 - 2.60
LSD vs SLS		0.53	1.28	0.38 - 6.99
FSD vs SLS		1.00	1.04	0.26 - 3.83
LSD vs FSD	Pelvic Tilt	0.24	0.48	0.11 - 1.84
LSD vs SLS		0.55	1.47	0.38 - 5.88
FSD vs SLS		0.76	0.71	0.18 - 2.61
LSD vs FSD	Hip Flexion	0.21	0.41	0.08 - 1.74
LSD vs SLS		0.51	1.68	0.38 - 8.14
FSD vs SLS		0.76	0.69	0.17 - 2.66
LSD vs FSD	Knee Flexion	0.32	2.17	0.49 - 10.58
LSD vs SLS		0.55	1.47	0.38 - 5.88
FSD vs SLS		0.12	3.21	0.78 - 15.04
LSD vs FSD	Trunk Lean	0.36	2.03	0.53 - 8.18
LSD vs SLS		0.54	0.58	0.14 - 2.22
FSD vs SLS		1.00	1.19	0.31 - 4.54
LSD vs FSD	Pelvic Drop	0.54	1.52	0.38 - 6.30
LSD vs SLS		0.37	0.55	0.13 - 2.16
FSD vs SLS		1.00	0.84	0.22 - 3.11
LSD vs FSD	Hip Adduction	1.00	0.86	0.21 - 3.36
LSD vs SLS		0.53	1.69	0.41 - 7.11
FSD vs SLS		0.75	1.45	0.36 - 5.97
LSD vs FSD	Knee Abduction	0.73	1.55	0.34 - 7.59
LSD vs SLS		0.73	1.42	0.29 - 7.22
FSD vs SLS		1.00	1.09	0.24 - 4.94

Table 2
Results of Fisher's exact tests for the association of single subjects having symmetry between tasks. Odds ratios and confidence intervals (CI) imply the direction of the association (odds ratio >1 = asymmetry in both tasks, odds ratio <1 = symmetry in both tasks).

Tasks	Variable	p-value	odds ratio	CI
LSD vs FSD	Trunk Flexion	0.63	1.93	0.18–20.56
LSD vs SLS		0.33	0.24	0.00–3.01
FSD vs SLS		1.00	0.67	0.07 - 5.02
LSD vs FSD	Pelvic Tilt	0.36	3.29	0.38–45.61
LSD vs SLS		0.65	0.53	0.05 - 4.20
FSD vs SLS		0.41	0.43	0.05 - 2.96
LSD vs FSD	Hip Flexion	0.61	2.38	0.21–36.66
LSD vs SLS		0.60	0.33	0.01–4.53
FSD vs SLS		0.68	1.47	0.19 - 11.68
LSD vs FSD	Knee Flexion	0.61	1.78	0.10–30.66
LSD vs SLS		0.07	0.10	0.00–1.16
FSD vs SLS		0.15	5.81	0.45–336.27
LSD vs FSD	Trunk Lean	0.67	0.64	0.07 - 5.22
LSD vs SLS		1.00	0.89	0.11 - 7.17
FSD vs SLS		1.00	1.07	0.14 - 7.72
LSD vs FSD	Pelvic Drop	0.65	1.72	0.20 - 16.75
LSD vs SLS		0.36	3.14	0.35–44.12
FSD vs SLS		0.01*	11.52	1.34–172.78
LSD vs FSD	Hip Adduction	0.39	2.38	0.30 - 20.97
LSD vs SLS		1.00	1.00	0.10 - 8.72
FSD vs SLS		0.36	2.78	0.33 - 27.25
LSD vs FSD	Knee Abduction	0.29	3.70	0.32–46.72
LSD vs SLS		0.54	3.04	0.17–55.71
FSD vs SLS		0.01*	16.56	1.16–1038.60

*significant relationship between tasks ($p < 0.05$).

was found during the LSD when 12 of the 14 participants with bilateral differences had increased pelvic drop on the non-preferred leg. To test the supposition that interlimb differences were canceled out, a post-hoc interlimb test was run that accounted for participants who had statistically greater knee abduction on the preferred leg (Fig. 5). When participants with greater knee abduction on the preferred leg (as determined by the single subject analyses) had their preferred and non-preferred legs switched for interlimb analyses, a statistical difference was found ($p < 0.01$, 5-89%). Although, this post-hoc analysis was not conducted for each task and variable, the result exemplifies the potential for intraparticipant variability to influence interlimb analyses. A future alternative to running post-hoc tests may be to include a visual assessment of performance prior to motion capture analyses. Including this step may better stratify legs when performing interlimb kinematic analyses as clinical ratings of stability for these tasks have been found valid in relation to kinematic data (Rabin, Portnoy, & Kozol, 2016; Whatman, Hume, & Hing, 2015).

Classifying limb preference based on the current study's task specific method may not have been adequate for identifying potential movement asymmetries with interlimb analyses. Participant identification a most-stable leg did not align with movement patterns often considered to be mechanically stable. During single leg movement tasks, the center of mass migrates medially; thus, increased demands are placed on the musculature of the hip to resist the force of gravity (Kulmala et al., 2017). When adequate muscular control strategies are not adopted, increased frontal plane motion may occur, placing increased demands on the passive structures of the hip and knee (Saki, Tahayori, & Bakhtiari Khou, 2022). Thus, clinicians should be aware that some individuals may perceive increased stability using a movement pattern that relies more on the passive structures of the hip and knee. Perception of

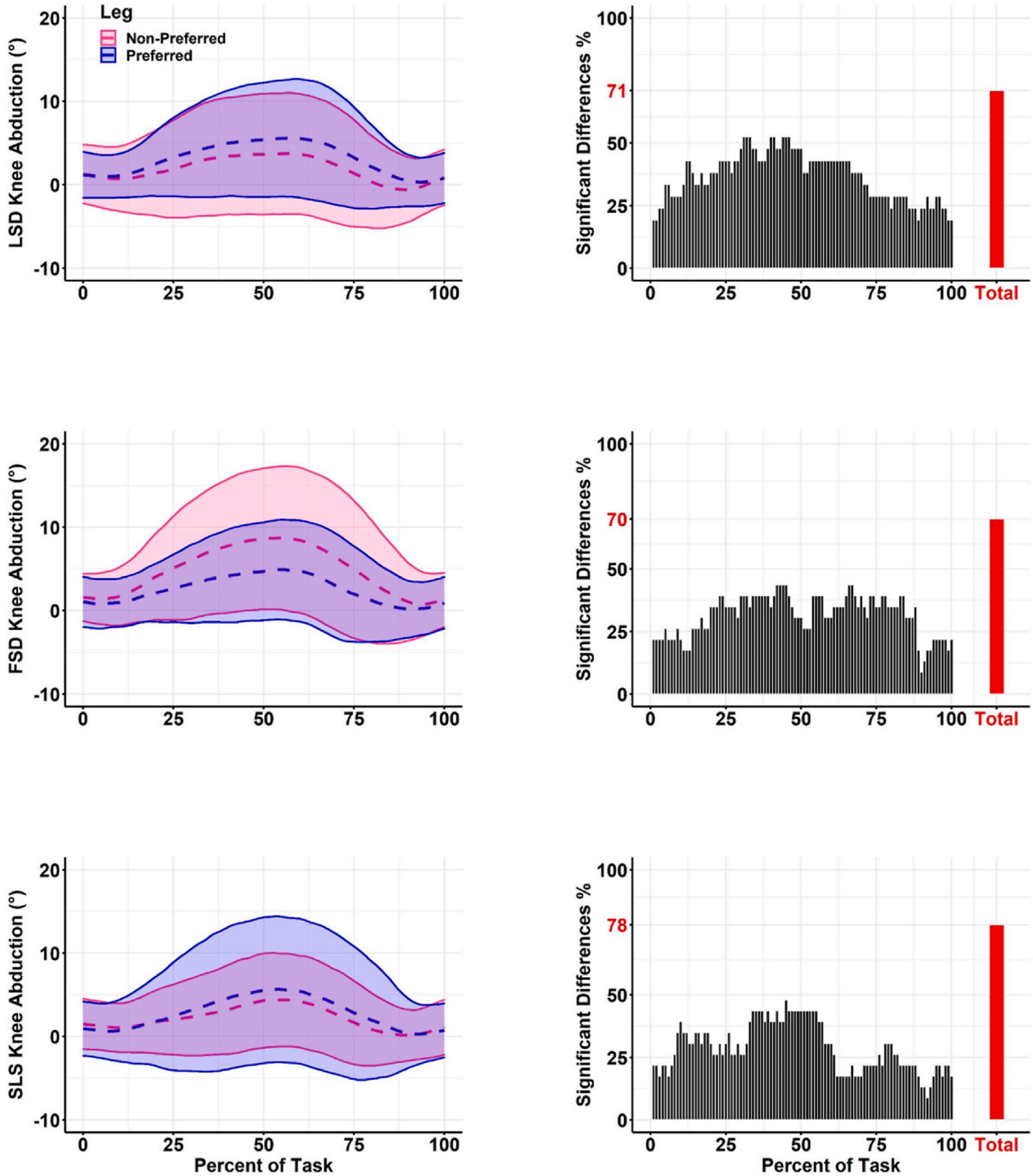

Fig. 4. Left column plots display time series for interlimb comparisons of knee abduction for the lateral step down (LSD), forward step down (FSD), and single leg squat (SLS). The right column plots demonstrate the results of the single subject analyses. Black bars represent the percentage of participants with a statistical bilateral difference at each percentage of the task. The red bar and red value on the y-axis indicate the overall percentage of participants with a difference between legs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

stability may also have been influenced by performing step down tasks, as the current study found a relationship between the selection of the preferred leg during the FSD and LSD. However, the premise of limb dominance being task specific may still be supported as relationships were not found between the SLS and the other two tasks. Further, 10 of our 23 participants had a disagreement about their preferred limb across the three tasks.

The single subject analyses were also used to assess the purpose of determining whether specific tasks were more associated with kinematic asymmetries. A main finding from this investigation was that no task was found to have a greater association with having an asymmetry (or not) than another task (Table 1). Other studies examining symmetry across multiple tasks have also found little (Bishop et al., 2020) or no (Loturco et al., 2018) association of task on measures of symmetry. Although findings from the current study do not implicate the presence of asymmetry in healthy individuals, there was also no evidence found that suggests participants had a greater probability of being symmetrical for a given task. As one task did not stand out, multiple tasks may be necessary for the overall assessment of whether an apparently healthy individual has asymmetrical movement patterns. This information is not only valuable for clinical evaluations of symmetry, but longitudinal studies examining the potential of asymmetry to increase the likelihood of injury risk. Current systematic reviews have found moderate to low evidence that asymmetries have a causal relationship with injury

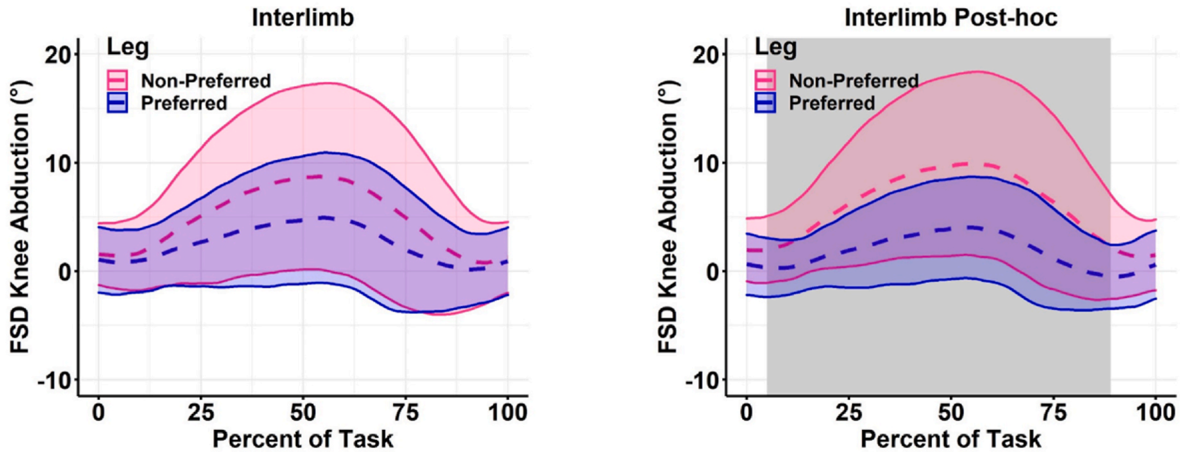

Fig. 5. Left plot displays time series for interlimb comparisons of preferred and non-preferred legs for knee abduction during the Forward Step Down (FSD). Right plot displays interlimb post-hoc analysis. For the post-hoc test, non-preferred legs were defined as the legs with increased knee abduction as determined by the single subject analyses, or the non-preferred leg when single subject analyses did not determine a difference between legs. The shaded gray region indicates time of significant difference.

(Helme, Tee, Emmonds, & Low, 2021). Of the tasks examined in the current study, the SLS has been the sole task used to examine for the relationship of asymmetrical movement patterns to injury risk (Petushek, Nilstad, Bahr, & Krosshaug, 2021; Räisänen et al., 2018). Findings from the longitudinal studies found no association between injury risk and movement asymmetries during a SLS (Petushek et al., 2021; Räisänen et al., 2018). However, evidence from the current study and prior investigations (Bishop et al., 2020; Loturco et al., 2018) suggests that multiple tasks may be needed to assess asymmetries and should be considered by future longitudinal studies assessing the association of asymmetrical movement patterns and injury risk.

Although none of the tasks were found to be associated with a higher probability of having an asymmetry, two associations were found between the FSD and SLS tasks for whether a participant had or did not have an asymmetry for frontal plane hip and knee motion (Table 2). These findings indicate that given symmetry or asymmetry is known during the FSD or SLS it is probable that the patient or participant will display the same level of symmetry in the other task. A prior manuscript from this data set that investigated the effect of task using only the preferred leg (Martonick et al., 2022) found that the same participants performed the SLS with greater vertical center of mass (COM) displacement and hip flexion when compared to the FSD. Interestingly, the FSD had increased frontal plane knee motion compared to the SLS. As greater vertical COM displacement is thought to place greater demand on the musculature of the hip and pelvis (Harris-Hayes et al., 2020), it was postulated that the increased knee abduction during the FSD was a result of the movement pattern for the tasks demands and not weakness of the musculature of the hip and pelvis. Similarly, bilateral differences may not be a result of the demand placed on the musculature as the two tasks were found to have an association for the presence of movement asymmetries. Thus, training to improve symmetry may want to include neuromuscular interventions that target the movement pattern, rather than strength training alone.

This study has several limitations to consider. First, we assessed a population of apparently healthy individuals without regard for training backgrounds. In populations with a more homogeneous training background, or a similar history of pathology, asymmetries may be more likely to occur with interlimb analyses. However, both elite athletes (Bishop et al., 2020; Loturco et al., 2018) and non-athletes (Carcia et al., 2019) have been found to have task and variable specific asymmetries. Next, kinematic trajectories are subject to error from marker placement, specifically in the frontal and transverse planes (Alenezi, Herrington, Jones, & Jones, 2016; McFadden, Daniels, & Strike, 2020). As it has been demonstrated that errors in marker placement can be limited by having a single practitioner apply the reflective markers (Pohl et al., 2010), all pelvis, hip, and knee markers were applied by a licensed clinician trained in the palpation of anatomical landmarks. Lastly, the single subject analysis may have been underpowered to detect smaller changes due to the small sample size (i.e., 5 trials on each leg). Using statistical models, 5-10° differences in kinematics have previously been reported to have a range of power from 0.5 to 0.75 for a sample size of five (Luciano, Ruggiero, & Pavei, 2021). Thus, the current number of trials for the single subject analyses may have suffered from type II errors. Future analyses looking at differences greater than 5° may want to consider at least 7 trials to achieve a power of 0.8 (Luciano et al., 2021). Nevertheless, a meaningful amount of time above the critical threshold and the timing where it is crossed has not been established. For the current study, we defined any participant who had a single data point above the critical threshold as having a bilateral difference and used this as a binary variable for the Fisher's exact tests. While there were statistically significant associations and ORs that exceeded one and did not have a value of one for the CIs, the CIs were large which may be attributable to our relatively small sample size.

In conclusion, movement pattern asymmetries were largely nonexistent at the interlimb level. While this finding can't be ignored, the single subject analyses provided evidence that the null findings of the interlimb model may have been influenced by the variability of movement patterns on the leg that was perceived as the most stable. Future study's should consider more objective measures of limb performance when stratifying the lower extremity for investigations of interlimb symmetry. Assessments of symmetry should also involve multiple tasks as no single task was found to have an association with the presence or absence of symmetrical movement patterns. Likewise, for most kinematic variables, asymmetries were found to be task specific.

Declaration of competing interest

None.

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