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Comparison of Three Single Leg Weightbearing Tasks with Statistical Parametric Mapping

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Abstract: The single leg squat (SLS), forward step down (FSD), and lateral step down (LSD) are clinically reliable movement screens for identifying motion imbalances. The current understanding for the kinematic profiles of each task is limited to discrete time points such as peak knee flexion. However, analyses of the entire movement would better aid clinicians when selecting the appropriate task for rehabilitation or movement screen purposes. The current study used Statistical Parametric Mapping to ascertain differences in the kinematic waveforms for the entire duration of each task. The trunk, pelvis, hip, and knee were analyzed in the sagittal and frontal planes. Data for each variable and task were analyzed from 0–100% of the movement. Primary findings indicated that the FSD provoked a greater magnitude of knee abduction than the SLS and LSD from 26–66% of the movement. The SLS generated the greatest amounts of trunk, pelvic, and hip flexion for the entirety of the movement. The LSD elicited the least amount of ipsilateral trunk lean (90–100%). Thus, the FSD may be optimal for assessing frontal plane knee motion as a screen for injury risk, while the SLS has potential to place increased sagittal plane demand on the muscles of the hip.

Keywords: SPM; movement screens; rehabilitation; kinematics

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1. Introduction

Single leg movement tasks are of interest to practitioners for evaluating dynamic joint alignment during movement screens, tracking rehabilitation progress, and as exercises [1]. The single leg squat (SLS), forward step down (FSD), and lateral step down (LSD) are movement screens found to be clinically reliable and valid for identifying motion at the trunk, pelvis, hip, and knee when weight-bearing on a single limb [1,2]. The assessment of joint alignments is similar during these movement screens; however, the FSD and LSD are performed from a 15–25 cm tall box that constrains the movement [1,3,4]. In contrast, clinical use of the SLS often has patients lower themselves to a self-determined depth [1,5]. Another difference between the tasks is that the LSD is performed with the weight-bearing foot parallel to the edge of the box while the FSD places the foot in a perpendicular orientation [3,4]. Differences in task demands may lead to specific kinematic alignments of the trunk and lower extremities [6]. Insights for kinematic alignment differences between the SLS, FSD, and LSD may help practitioners when selecting between tasks for movement screens, rehabilitation, and exercise.

Prior to administering single leg weight-bearing tasks, practitioners should have evidence for how the subtle differences between task demands influence trunk, pelvis, hip, and knee kinematics. For example, positioning of the non-weight-bearing leg may influence hip and knee mechanics on the contralateral leg [7–9]. The increase in hip flexion on the non-weight-bearing leg during the FSD (and variations of the SLS) is thought to position the center of mass (COM) more anteriorly [7,8]. In turn, this may require greater hip extension from the stance limb to mitigate the anterior migration of the COM and maintain anterior-posterior stability [7]. A comparison of the FSD and LSD, demonstrated greater knee flexion occurred on the weight-bearing leg occurred during the FSD [7]. The reported increase for knee flexion during the FSD may make it a better task than the LSD for inducing quad and gluteal activation [10]. Kinematic differences have also been reported during variations of the SLS where the positioning of the non-weight-bearing leg in a flexed position decreased peak trunk flexion when compared to placing the non-weight-bearing leg in a neutral position [5,9]. Tasks that limit trunk flexion could be important when it is necessary to reduce loads at the anterior cruciate ligament (ACL) [11]. Excessive knee abduction and pelvic drop are movement patterns that have also been attributed to increased loads at the knee [12,13]. As this pattern has been associated with decreased hip muscle function [14], a task that better invokes knee abduction and pelvic drop would be useful when screening for hip muscle performance.

While there is current evidence supporting movement pattern differences among these tasks; it has been based on discrete kinematic analyses. For example, prior investigations of these tasks have focused on the event identified at 60° of knee flexion [5,6,9], or the event of peak knee flexion for analysis [7,15]. By reducing one-dimensional vector data into a zero-dimensional scalar, prior approaches omit the analysis of various movement patterns that can be used to accomplish the different tasks. This approach may result in missed differences between tasks [16,17]. Performing discrete analyses on vector data can also produce false positives at high rate [18]. A proposed alternative to discrete analyses is Statistical Parametric Mapping (SPM), which can be used to assess differences in kinematic waveforms for the duration of tasks and reduce false positives when examining movement data [18,19]. Expanding analyses to the entire movement interval better reflects how a practitioner would evaluate the movement and may improve the understanding of strategies used to accomplish the different tasks [20]. Therefore, implementing an SPM analysis for comparisons of the SLS, FSD, and LSD would provide more robust statistical comparisons, as well as more a practical assessment of the movement pattern.

The purpose of this study was to assess for potential differences in the movement patterns of healthy individuals during the SLS, FSD, and LSD. To identify differences between tasks, kinematic waveforms in the fontal and sagittal plane at the trunk, pelvis, hip, and knee were analyzed with SPM analyses. It was hypothesized that while performing the SLS, participants would have greater frontal plane motion at the hip and knee. A secondary hypothesis was that the positioning of the non-weightbearing leg during the FSD would result in less sagittal plane motion at the trunk, hip, and pelvis.

2. Materials and Methods

2.1. Participants

A convenience sample of 11 female (21.3 ± 1.8 years, 167.5 ± 4.4 cm, 62.3 ± 9.9 kg) and 10 male participants (24.6 ± 3.6 years, 180.3 ± 6.5 cm, 78.6 ± 13.6 kg), were recruited from the local community. To be included, participants had to be free from current self-reported injury, and able to perform the SLS to 60° of knee flexion while maintaining their hands on their waist as a sign of being clinically rated as 'good' [5]. Participants with low back, or lower extremity pain during any of the tasks were excluded. Previous history of lower extremity or low back surgery also excluded participants. 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 asked to perform FSD, SLS, and LSD on each leg. All tasks were performed with the participant's personal athletic footwear. Participants performed repetitions on each leg until they were comfortable with the task. They were then asked to identify which leg they felt more stable on. As leg dominance has been shown to be task-specific [21,22], the self-identified 'more stable' leg was set as the participant's preferred leg for that task and used for analysis. Participants were then fitted with a custom full-body cluster-based reflective marker set that defined the trunk, pelvis, thighs, and shanks as rigid segments. Calibration markers at the knee, and pelvis markers were applied by a single investigator to maintain a consistency of measurement [23]. Trials were collected with an 8-camera motion capture system (250 Hz, Vantage, Vicon Motion Systems Ltd., Oxford, UK). For the data collection, participants were asked to perform each task up to eight times to achieve five 'good trials'. A trial was rated as 'not good' and recollected if the participants hands came off their waist, they performed the trial in a jerky or non-continuous manner, or lost balance during the task [5]. Participants completed all trials (both legs) of a single task prior to changing tasks. A preliminary analysis revealed that participants had increased pelvic drop on the non-preferred leg during the LSD; however, no other bilateral differences were observed. Thus, the preferred leg may have represented the participant's most stable leg. The order of the tasks and legs was randomized across participants to account for potential learning effects and fatigue.

The SLS was performed to the depth the participant could achieve while still performing one continuous and smooth motion as determined by the researcher. The non-weightbearing leg was placed in a neutral hip position with the knee bent to approximately 90° [5]. This SLS position was selected because the non-weightbearing hip was in a similar position to the LSD. 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 toes at the edge of the box and asked to dorsiflex their non-weightbearing foot, lightly touch their heel to the ground, and return to their starting position in one continuous motion [3,24]. No instructions were given to adjust kinematic alignments. The LSD was performed with the medial aspect of the weight-bearing foot placed parallel to the edge of the box [24], following the same instructions as the FSD. Visual 3D images for each of the tasks is provided in Figure 1.

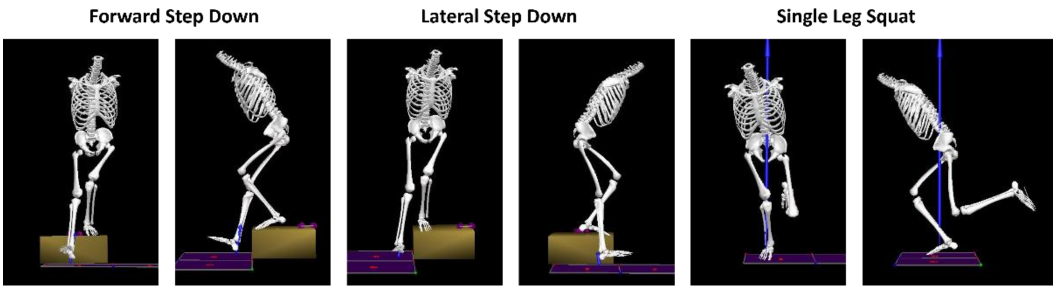

Figure 1. Visual 3D model representing the forward step down, lateral step down, and single leg squat tasks. Images are presented with frontal and sagittal plane views for each task.

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). 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 [25]. The pelvis was modeled as a CODA pelvis and pelvis segment angles were calculated relative to the global coordinate system following Baker [19]. 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 were represented as anterior pelvic tilt. Ipsilateral trunk lean was defined as a positive value and indicates frontal plane motion toward the weightbearing leg. Positive values were used to represent trunk, hip, and knee flexion. Hip adduction and knee abduction were also represented by positive values. The center of mass (COM) was estimated by Visual 3D using each of the segments. Vertical COM displacement was calculated from its position at the start of the movement to the lowest position relative to the lab for each of the three tasks.

Marker trajectories were low-pass filtered using a fourth-order Butterworth filter at 6 Hz [6,9]. Kinematic time-series were interpolated to 100% of the movement for the SPM analysis from the beginning to the end of the task using a custom MATLAB script (Version 2021b, 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 three standard deviations from the quiet stance period. The end of the task was defined as the point when hip flexion returned to that starting value. Vertical displacement of the COM was calculated as the difference between the peak and minimum vertical position during each trial.

2.4. Statistical Analysis

All SPM analyses were conducted in MATLAB using an open-source software package spm1D 0.4 [26]. Separate within-subjects repeated measures analysis of variance (ANOVA) were first performed to compare the effect of task on sex. When considered separately, males and females demonstrated similar differences between tasks; thus, males and females were combined into one group. Individual ANOVA tests were then performed on all angular kinematic data to compare the effect of task for each variable. Additionally, we performed paired t-tests between tasks when main effects were observed. The significance level for all statistical tests was set a priori to $p < 0.05$. A Bonferroni correction was not deemed appropriate due because the procedure requires independence across the tests which is not the case with time-series data [20]. The null hypotheses were rejected if the computed F-value (or *t*-value for paired *t*-tests) exceeded the critical threshold. Statistical models are based on a model of randomness and the probability that random data would produce the observed result [27]. With an SPM model, the randomness is computed from the waveform and the critical threshold is the statistical probability that the observed trajectories are not random. Thus, when the time series exceed the F-value of the random data (i.e., the critical threshold) the waveforms were considered statistically different. The COM vertical displacement was analyzed as a discrete variable because only the depth of which each task was performed was of interest. The COM displacement was compared between tasks using a within-subjects repeated measures ANOVA and followed up with t-tests.

3. Results

The SPM ANOVAs indicated differences for hip flexion, anterior pelvic tilt, trunk flexion, knee abduction, and ipsilateral trunk lean were present. Post hoc tests indicated that greater hip flexion ($p < 0.01$), pelvic tilt ($p < 0.01$), and trunk flexion ($p < 0.01$) occurred across more than 90% of the movement when the SLS was compared to both the FSD and LSD (Figures 2–4). When performing the LSD, participants demonstrated increased pelvic tilt ($p = 0.02$, 6–40%, Figure 3) and trunk flexion ($p = 0.04$, 6–15%, Figure 4) when compared to the FSD. Participants also performed the FSD with greater knee abduction (Figure 5) compared to both the LSD ($p < 0.01$, 40–66%) and SLS ($p < 0.01$, 26–62%). The LSD was found to have reduced trunk lean ($p < 0.01$) relative to both the FSD and SLS during the last 10% of the task (Figure 6). The COM vertical displacement was changed between each of the task comparisons (FSD-LSD, $p < 0.01$; FSD-SLS, $p = 0.04$; LSD-SLS, $p < 0.01$). The SLS had the greatest vertical COM displacement (24.9 ± 5.1 cm), followed by the FSD (21.6 ± 1.3 cm), and LSD (19.0 ± 1.0 cm).

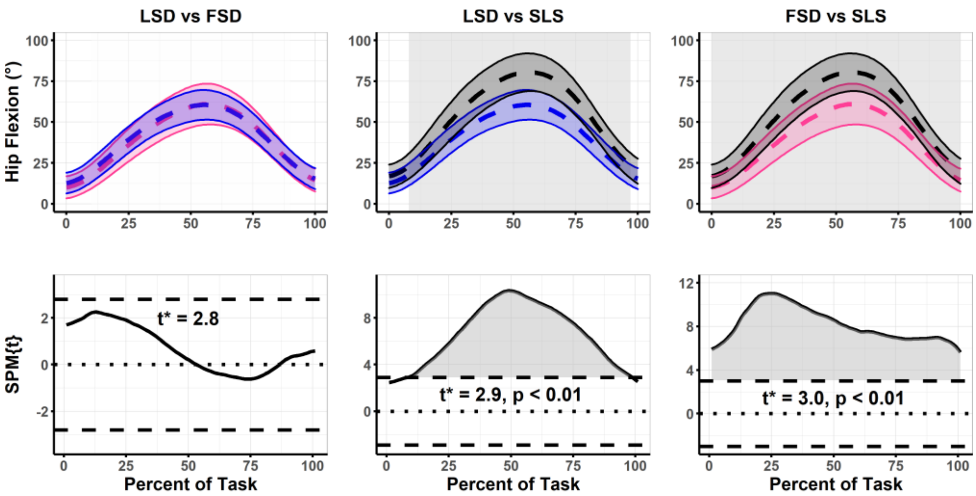

Figure 2. Kinematic waveforms for hip flexion. Blue = LSD, Pink = FSD, Black = SLS. Shaded areas indicate significant differences. Below: SPM t-tests, dashed lines indicate threshold for significant differences; shaded areas indicate where the threshold was exceeded.

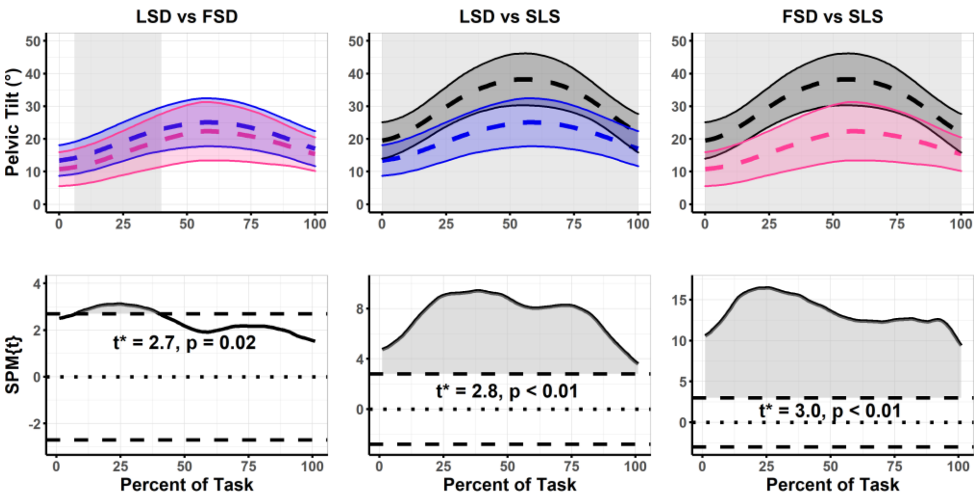

Figure 3. Kinematic waveforms for anterior pelvic tilt. Blue = LSD, Pink = FSD, Black = SLS. Shaded areas indicate significant differences. Below: SPM t-tests, dashed lines indicate threshold for significant differences; shaded areas indicate where the threshold was exceeded.

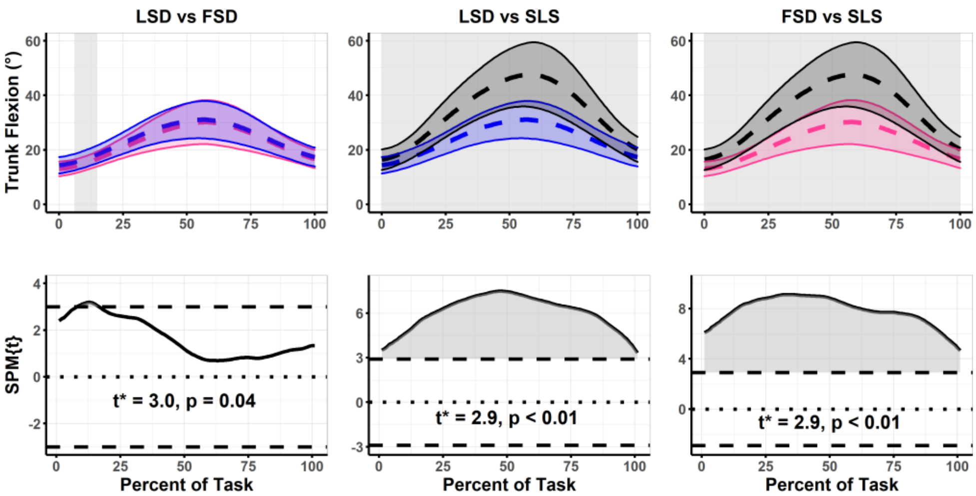

Figure 4. Kinematic waveforms for trunk flexion. Blue = LSD, Pink = FSD, Black = SLS. Shaded areas indicate significant differences. Below: SPM t-tests, dashed lines indicate threshold for significant differences; shaded areas indicate where the threshold was exceeded.

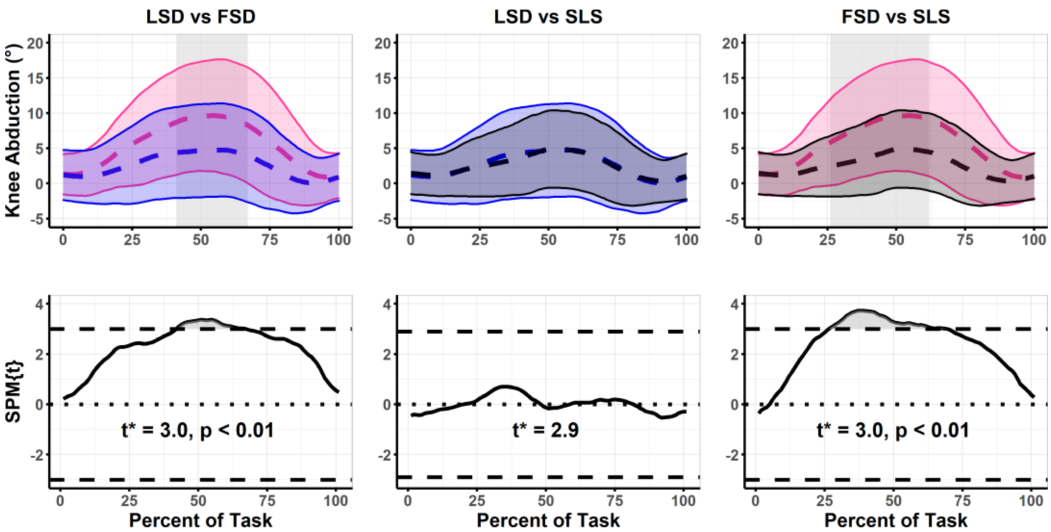

Figure 5. Kinematic waveforms for knee abduction. Blue = LSD, Pink = FSD, Black = SLS. Shaded areas indicate significant differences. Below: SPM t-tests, dashed lines indicate threshold for significant differences; shaded areas indicate where the threshold was exceeded.

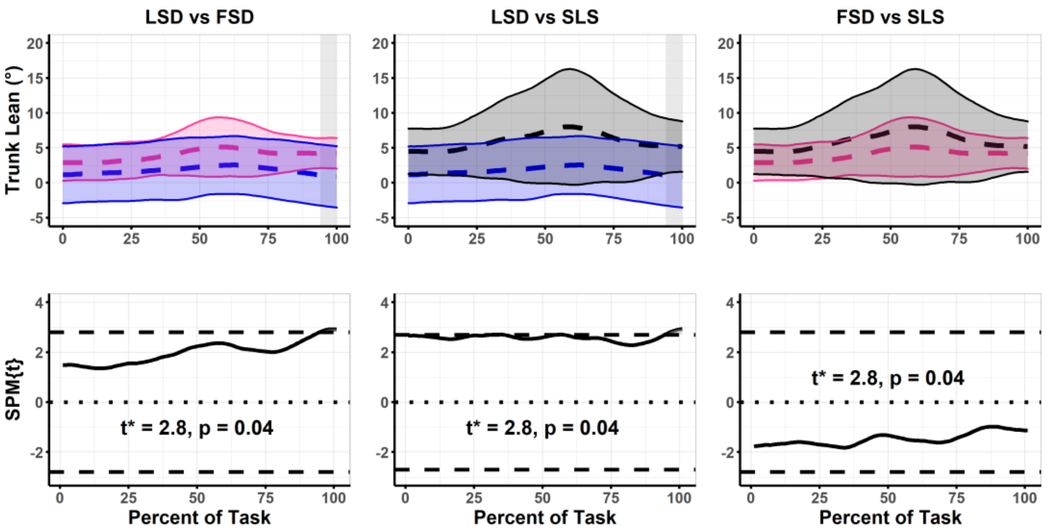

Figure 6. Kinematic waveforms for ipsilateral trunk lean. Blue = LSD, Pink = FSD, Black = SLS. Shaded areas indicate significant differences. Below: SPM t-tests, dashed lines indicate threshold for significant differences; shaded areas indicate where the threshold was exceeded.

4. Discussion

Analyses of the entire duration of the SLS, FSD, and LSD tasks enabled the detection of differences at different time points between the movements as well as the vertical displacement of the COM. Interestingly, the greater vertical displacement of the COM during the SLS did not result in greater knee abduction than the other two tasks. Thus, the hypothesis that participants lowering themselves to a self-determined depth during the SLS would invoke greater magnitudes of frontal plane motion at the hip and knee than both the FSD and LSD was rejected. Assessing the overall movement patterns revealed that performing the FSD resulted in greater knee abduction than the other two tasks from 26–62% of the movement. Similar knee abduction waveforms for the SLS and LSD also suggested that squatting lower on a single leg did not affect frontal plane knee motion. Excessive knee abduction during the SLS is often considered a risk factor for injury [28] and may be attributed to inadequate strength of the hip musculature [15,29]. As hip abductor weakness has also been associated with a decreased SLS depth [30], it is likely that factors other than hip muscle strength were responsible for the increased knee abduction during the FSD. For example, the non-weightbearing hip was in a flexed position during the FSD and a neutral position for the other tasks. Therefore, the placement of the non-weightbearing leg may have elicited greater knee abduction during the FSD. Although increased knee abduction angles have not been previously reported, increases in hip adduction angles during the FSD in comparison to the SLS [6,15] and LSD [7] have been found. Participants in the current study had mean peak hip adduction angles for the FSD (17.4 ± 6.7°) and LSD (14.7 ± 5.7°) similar to what has been previously supported as a difference (FSD = 18.5 ± 4.2°, LSD = 17.1 ± 4.0°) [7]. Thus, practitioners and researchers may want to select the FSD when screening for individuals with excessive knee abduction.

The increased magnitude of hip flexion during the SLS was likely a result of allowing the participants to squat as deep as they could while maintaining a perceived smooth and stable motion. Controlling the depth of the SLS with knee position has previously been found to elicit similar hip angles for both the FSD and SLS [31]. In contrast, the current study's population had increased hip flexion angles during the entire waveform of the SLS when compared to the FSD, which supports our hypothesis that the FSD would have less sagittal plane motion. The SLS having increased hip flexion across the entire waveform also suggests that the kinematic timing of the analysis or a reduced squat depth would not have affected the current results. Although hip flexion was increased during the SLS and the SLS had the greatest vertical COM displacement, it does not appear that knee flexion was a primary contributor to the differences in COM displacement as the SPM analyses for knee flexion were similar across tasks. Therefore, individuals performing this version of the SLS may use a more hip dominate strategy to lower their COM. The SLS could be used as part of an assessment in patients with femoral acetabular impingement (FAI), due to the populations reluctance to perform hip flexion on the affected leg [30,32]. Additionally, the increased sagittal plane demand and depth of squat during the SLS make it an optimal exercise when training to increase performance during jumping tasks [33].

While increased trunk and pelvic kinematics may not be directly involved in lowering the COM during squatting tasks, they are often considered as markers of movement quality during these tasks [1,34]. Excessive trunk movement is often considered a risk factor due to the subsequent increase in mechanical demand at the hip and knee [35,36]. For example, increased trunk flexion has been associated with greater hip extensor moments during the stance phase of gait [36]. The current study findings of increased trunk and pelvic motion during SLS may have resulted in greater torque at the hip throughout the movement than found with the FSD and LSD. Additionally, the LSD may place greater torque on the hip than the FSD during the eccentric phase of the movement which also supports our hypothesis that positioning of the non-weightbearing leg would result in reduced flexion at the trunk and pelvis. Thus, the FSD may be an appropriate task for patients with low back pain due to a reluctance to flex the lumbar spine during stepping tasks [37]. The FSD may also be useful when practitioners are aiming to reduce hip torque in patients with FAI during rehabilitative exercises.

Trunk motion was also different between tasks in the frontal plane as participants demonstrated less ipsilateral trunk lean during the LSD. While this difference only became statistically significantly in the last 10% of the task, the t-statistic touched (but did not exceed) the critical threshold multiple times compared to the SLS (Figure 6). As ipsilateral trunk lean during steady standing on a single leg has been correlated with increased knee abduction moments [38], the LSD task may be more appropriate for knee rehabilitation exercises with a need for reduced frontal plane torque. For example, individuals with patella femoral pain syndrome (PFPS) who have increased ipsilateral trunk lean during the SLS [39] may place less torque on the pathological knee during the LSD. Thus, clinicians may want earlier stages of PFPS rehabilitation to use the LSD and then progress to exercises like the FSD and SLS.

The current study has several limitations. It is possible that the self-identified most stable leg (i.e., preferred) was not the most stable leg from a mechanical perspective. Although we found minimal differences between preferred and non-preferred legs, group data has been shown to mask bilateral differences [40]. Future work should consider using a single subjects design to determine the most stable leg prior to group analysis. Similar to other studies on SLS, FSD, and LSD, we used a single rigid segment to model the trunk [5,6]. More complex models exist [41] and may have better represented differences between tasks at the trunk. Lastly, although the SPM waveform analysis has been shown to reduce the likelihood of false positives when compared to the discrete analysis of kinematic trajectories [18], the statistically significant findings in this study do not necessarily imply practical meaningfulness. Currently there is no statistical measure of effect sizes when using an SPM analysis that may help interpret magnitude of these differences.

5. Conclusions

The current study examined differences between the movement patterns of the SLS, FSD, and LSD using waveform analyses. Although participants lowered their COM furthest during the SLS, it did not result in greater knee abduction than the other tasks. Instead, the FSD best elicited frontal plane knee motion. Additionally, the FSD had limited flexion at the trunk, pelvis, and hip. During the LSD participants had reduced ipsilateral trunk lean. The results indicate that changes between leg position and tasks demands altered movement patterns between the three tasks. Practitioners should consider using the FSD when assessing injury risk due to excessive knee abduction. Whereas the SLS could be the best suited of the three tasks to strengthen the hip in the sagittal plane. The LSD may be the most applicable task for limiting torque at the knee when training lower extremity movement patterns.

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Data Availability Statement: Data can be made available upon request to the authors.

Conflicts of Interest: The authors declare no conflict of interest.

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