Novel Approaches for Analyzing Single Leg Movement Screens and Applications for Clinical Practice

A Dissertation

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by

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Abstract

Single leg movement screens provide valuable information to practitioners when evaluating unilateral weightbearing control. The ability to maintain proper alignment of the trunk, pelvis, and lower extremity are often assessed during single leg movement screens such as the single leg squat (SLS), forward step down (FSD), and lateral step down (LSD). Each of these tasks examine an individual's ability to lower and raise their center of mass while maintaining balance and proper mechanics (i.e., upright trunk position, neutral pelvis). Movement patterns identified by these tasks such as ipsilateral trunk lean, pelvic drop, and knee valgus that are known to place excessive forces on lower extremity joints and considered to be a sign of inadequate motor control. The ability of these tasks to identify the abovementioned factors provides utility for practitioners when screening movement and tracking the rehabilitation process. Additionally, the unilateral nature of the SLS, FSD, and LSD allow for the analysis of bilateral differences that may be associated with increased injury risk.

Current research supports the idea that healthy individuals have symmetrical lower extremity movement during single leg weightbearing movements. Thus, rehabilitation protocols often assume symmetry prior to the injury and subsequently will utilize the unaffected leg as a benchmark for treatment goals. However, conventional research has focused on group analyses that have been found to obfuscate asymmetrical movement patterns that are occurring at the individual level. The masking of asymmetrical movement patterns at the group level is due to the dichotomization of legs by the dominant (i.e., the leg used to kick a ball) and non-dominant leg. Historically leg dominance, or preference, were arbitrarily selected as the dynamic leg used to kick a ball. However, this series of studies illustrates the importance of identifying a task specific method of identifying limb preference when performing clinical assessments from a group analysis perspective.

The overall purpose of this dissertation was to examine 1) potential differences in the movement patterns of three single leg weightbearing tasks (e.g., SLS, FSD, LSD), 2) whether performing these tasks resulted in asymmetrical mechanics, and 3) whether asymmetrical movement patterns could be corrected with an intervention. To address this purpose, two separate data collections were collected using convenience samples. The results of the first study provided the foundation for the clinical task used for the intervention of the culminating study.

The purpose of the first manuscript was to assess 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 of the trunk, pelvis, hip, and knee were analyzed. Primary findings indicated that the FSD provoked greater knee abduction than both the SLS and LSD. The SLS generated the greatest amount of sagittal plane motion at the trunk, pelvis, and hip for the entirety of the movement. The LSD elicited the least amount of ipsilateral trunk lean. Thus, the FSD may be optimal for assessing frontal plane knee motion as a screen for injury risk, while the SLS provided greater demand on the sagittal plane motion resulting in increased demand of the hip musculature.

The purpose of the second manuscript was to examine the ability of each task to elicit bilateral differences at the group and individual level. Kinematic waveforms in the fontal and sagittal plane at the trunk, pelvis, hip, and knee were analyzed to compare bilateral differences elicited during each task. Participants self-identified their preferred (perceived as most stable) and non-preferred legs for each task. Minimal differences occurred at the group level when comparing preferred and non-preferred legs during the FSD, LSD, and SLS. Performing the LSD on the non-preferred leg resulted in increased pelvic drop at the group level. There were no other significant group findings for the LSD, FSD, or SLS. At individual level, numerous differences were identified with the largest percentage of participants demonstrating asymmetries for frontal plane knee motion. Sagittal plane asymmetries were most common at the pelvis during the FSD. Individual analyses were necessary to illustrate the prevalence of asymmetrical movement patterns across tasks and participants.

The primary purpose of the final manuscript was to examine whether self-identified Total Motion Release® (TMR®) scores coincided with mechanical asymmetries during a SLS. The secondary purpose was to explore whether improving the subjective self-reported imbalances resulted in decreased movement pattern asymmetries. Sagittal plane mechanical waveforms for the SLS task were used to evaluate group and individual mechanical bilateral differences before and after the TMR® intervention. The study population included individuals who had bilateral difference scores greater than 10 on 0–100-point TMR® scale, with higher scores indicating a greater difference between legs. The leg that scored higher was classified as the non-preferred leg. When preferred leg was identified based on task specific criteria, reduced knee flexion, ankle flexion, and internal knee flexion moments were identified on the non-preferred leg for both group and individual analyses. After the intervention, subjective scores for dysfunction had equalized between legs. Additionally, participants had increased their internal knee flexion moments on the non-preferred leg. Bilateral differences for knee and ankle flexion, as well as knee flexion moments persisted following the intervention. In conclusion, practitioners should consider the potential of the TMR® protocol to improve self-perceived scores of dysfunction during a SLS; however, objective measures of movement should also be included when rehabilitative protocols intend to address mechanical imbalances.

The overall results of this dissertation indicate: 1) single leg movement tasks should not be used interchangeably, and the mechanical demands of each task may best suit specific screening or rehabilitative protocols, 2) incongruities between group and individual analyses indicated that it is necessary to include individual analyses when assessing movement pattern asymmetries, and 3) including objective measures of patient perceptions is required to dichotomize legs for group analyses. Future studies should begin to examine the importance of the observed movement asymmetries by considering individual analyses in conjunction with patient reported scales while performing longitudinal injury tracking.

Acknowledgments

Thank you to all the practicum students who helped with setting up and breaking down the equipment for data collections.

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For bringing me under your tutelage and enabling my abilities to question how movement is analyzed, and how these forms of analysis can improve patient care. Our discussions (and arguments) about research, and how we should interpret/apply our findings have been an instrumental part of my growth, and I hope we can continue to have these interactions for years to come. You are the Best!

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Dedication

Sarah, can you believe how far we have come?! This accomplishment does not get achieved without your love, devotion, and absolute awesomeness at everything you set your mind to (especially our family). Olyvia and Anton, you might not know this, but when life gets difficult, it is the thought of you two that reminds me to be thankful for everything I have been given. If my accomplishment here could achieve one thing, it would be to help you both understand that you can achieve your own goals.

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Statement of Contribution

Nickolai Martonick's specific contribution to this project included roles as lead author, primary responsibility as data collector, primary responsibility as data analyst, and primary director for study design.

Dr. Joshua Bailey's specific contribution to the project was as the major professor which included guidance on study design, analyzing data, and writing.

Dr. Russell Baker's specific contribution to the project was guidance on study design and writing.

Dr. Craig McGowan's specific contribution to the project was guidance on study design, analyzing data and writing.

Dr. Lindsay Larkins' specific contribution to the project was guidance on study design and writing.

Dr. Jeffry Seegmiller's specific contribution to the project was guidance on study design and writing.

Chapter 1:
Overall Dissertation Introduction

By

Nickolai J.P. Martonick

Introduction

Movement analyses are commonly used in sports medicine when developing injury prevention and rehabilitation protocols.[1] Control of the trunk, pelvis, and lower extremity are often assessed during single leg weightbearing tasks such as the single leg squat (SLS), forward step down (FSD), and lateral step down (LSD).[1,2] Each of the tasks examine an individual's ability to lower and raise their center of mass while maintaining balance and proper kinematic alignments (i.e., upright trunk position, neutral pelvis).[1] Inadequate motor control during these tasks can lead to movement patterns that include ipsilateral trunk lean, pelvic drop, and knee valgus.[1] When the abovementioned movement patterns occur during higher velocity activities such as running, and jumping, increased forces at the knee can lead to the risk of injury.[3] Motion capture analyses of single leg weightbearing tasks provide similar data to higher velocity movements such as jumping, running, and cutting.[4,5] As visual assessment of single leg tasks is associated with motion capture data,[6] the use of these tasks in clinical settings provides information about more ballistic movements, when injuries are more likely occur.[6] The relationship between the kinematics of single leg weightbearing tasks and higher velocity movements may also imply that improving kinematic alignment during these tasks is beneficial during situations with higher impact forces.

The SLS, FSD, and LSD each examine similar joint alignments; however, nuances in task demands may lead to meaningful differences between the kinematic profiles of each task. For instance, the FSD and LSD are performed from a 15-25cm tall box that constrains sagittal plane range of motion for the movement.[1] In contrast, clinical use of the SLS often has patients lower themselves to a self-determined depth.[7] 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.[6,8] Positioning of the non-stance leg may also be a factor as placing the non-stance leg in the anterior (FSD) and posterior (SLS) position likely influenced sagittal plane positioning of the center of mass (COM).[9,10] Whereas the placement of the leg under the COM during the LSD may have limit the task demand of mitigating COM translation in sagittal plane. Distinguishing how these nuances affect movement pattern differences between the SLS, FSD, and LSD would improve the selection of an appropriate task during clinical analyses.

The demands of single leg weightbearing tasks also make them ideal for the assessment of bilateral movement symmetry. Asymmetrical movement patterns are often thought to place apparently healthy individuals at risk of injury due to increased loads on the “dominant” leg, and a lack of stability on the “non-dominant” leg. However, the importance of lower extremity movement symmetry as it pertains to injury risk remains debated.[11] Nevertheless, clinicians will often use these tasks to assess lower extremity movement symmetry during the rehabilitation of patients who have injuries that limit movement on one side of the body.[12] The uninjured leg is often used as a benchmark for rehabilitation goals because it is assumed symmetry existed between legs prior to injury.[13,14] The assumption of symmetry in healthy individuals, or the assumed importance of symmetry, could lead to inadequate treatment goals. Therefore, it is necessary to examine whether apparently healthy individuals display movement symmetry during single leg weightbearing tasks, and which tasks may best identify asymmetrical movement. This task could then be used to further assess the importance of asymmetrical movement patterns.

The purpose of this dissertation is to examine the kinematic differences between the SLS, FSD, and LSD to identify the task that is best suited for a rehabilitation protocol designed to address sub-optimal movement patterns. To address the purpose, three protocols were designed to: 1) compare the kinematic profiles of the three tasks, 2) identify which of the three tasks is most sensitive to bilateral asymmetries, 3) explore the potential for a rehabilitative protocol to improve movement mechanics during the task that best identifies asymmetrical movement.

References

1. Ressman J, Grooten WJA, Rasmussen Barr E. Visual assessment of movement quality in the single leg squat test: A review and meta-analysis of inter-rater and intrarater reliability. *BMJ Open Sport Exerc Med*. 2019;5(1).

2. Whatman C, Hume P, Hing W. The reliability and validity of visual rating of dynamic alignment during lower extremity functional screening tests: a review of the literature. *Physical Therapy Reviews*. 2015;20(3):210-224.

3. Ugalde V, Brockman C, Bailowitz Z, Pollard CD. Single Leg Squat Test and Its Relationship to Dynamic KneeValgus and Injury Risk Screening. *PM and R*. 2015;7(3):229-235.

4. Whatman C, Hing W, Hume P. Kinematics during lower extremity functional screening tests-Are they reliable and related to jogging? *Physical Therapy in Sport*. 2011;12(1):22-29.

5. Munro A, Herrington L, Comfort P. The relationship between 2-dimensional knee-valgus angles during single-leg squat, single-leg-land, and drop-jump screening tests. *J Sport Rehabil*. 2017;26(1):72-77.

6. Rabin A, Portnoy S, Kozol Z. The Association Between Visual Assessment of Quality of Movement and Three-Dimensional Analysis of Pelvis, Hip, and Knee Kinematics During a Lateral Step Down Test. *Strength Cond J*. 2016;30(11):3204-3211.

7. Lewis CL, Foch E, Luko MM, Loverro KL, Khuu A. Differences in lower extremity and trunk kinematics between single leg squat and step down tasks. *PLoS One*. 2015;10(5).

8. Park KM, Cynn HS, Choung SD. Musculoskeletal Predictors of Movement Quality for the Forward Step-down Test in Asymptomatic Women. *Journal of Orthopedic and Sports Physical Therapy*. 2013;43(7):504-510.

9. Werner DM, Davis RW, Hinton A, Price SK, Rowland JL, Barrios JA. Three-dimensional joint kinematic and two-dimensional quality of movement comparison between lateral and forward step-downs. *Physical Therapy in Sport*. 2021;52:162-167.

10. Olivier B, Quinn SL, Benjamin N, Green AC, Chiu J, Wang W. Single-leg squat delicacies-the position of the nonstance limb is an important consideration. *J Sport Rehabil*. 2019;28(4):318-324.

11. Petu E, Nilstad A, Bahr R, Krosshaug T. Drop jump? single-leg squat? not if you aim to predict anterior cruciate ligament injury from real-time clinical assessment: A prospective cohort study involving 880 elite female athletes. *Journal of Orthopaedic and Sports Physical Therapy*. 2021;51(7):372-378.

12. Benjaminse A, Holden S, Myer GD. ACL rupture is a single leg injury but a double leg problem: Too much focus on “symmetry” alone and that’s not enough! *Br J Sports Med*. 2018;52(16):1029-1030.

13. Brown AM, Zifchock RA, Hillstrom HJ. The effects of limb dominance and fatigue on running biomechanics. *Gait Posture*. 2014;39(3):915-919.

14. 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*. 2017;27(11):1328-1336.

Chapter 2:

Comparison of Three Single Leg Weight Bearing Tasks with Statistical Parametric Mapping

By

Nickolai J.P. Martonick

Co-authored by

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and Joshua P. Bailey

Significance of the Chapter

The goal for the first study of this dissertation was to characterize the magnitudes of joint and segment motion for the single leg squat (SLS), forward step down (FSD), and lateral step down (LSD) tasks. Prior investigations into kinematic differences between the aforementioned tasks have limited analyses to a single time point within the duration of the tasks. However, limiting analyses to the timing of peak knee flexion, or when the knee reaches 60° of flexion, omits valuable information, and does not adequately describe the different strategies utilized to accomplish the task demands. Analyzing the whole task is necessary to identify movement patterns, and better reflects how practitioners assess movement. Therefore, the current study used a novel approach that analyzed the kinematic timeseries for the entirety of the three single leg weightbearing tasks. The comparison of tasks through timeseries provides practitioners and researchers information for not only if, but when the movement patterns during the SLS, FSD, and LSD become different. This information could then be used to select a task that best fits specific rehabilitation protocols, or that best identifies movement patterns thought to increase risk of injury.

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

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 15-25cm 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] This has been observed during a comparison of the FSD and LSD, when 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 different the 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 the positioning of the non-weightbearing leg during the FSD would result in less sagittal plane motion at the trunk, hip, and pelvis when compared with the other two movement screens. A secondary hypothesis was 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.

Methods

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.

Procedures

Prior to collecting data, participants were asked to perform FSD, SLS, and LSD on each leg. Participants performed repetitions on each leg until they were comfortable with the task demands for a single task and were able to identify which leg they felt most stable on while performing the task. All tasks were performed with the participant's self-selected athletic footwear on. As leg dominance has been shown to be task-specific,[21,22] the self-identified ‘most 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 (250Hz, 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 20cm 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] 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.

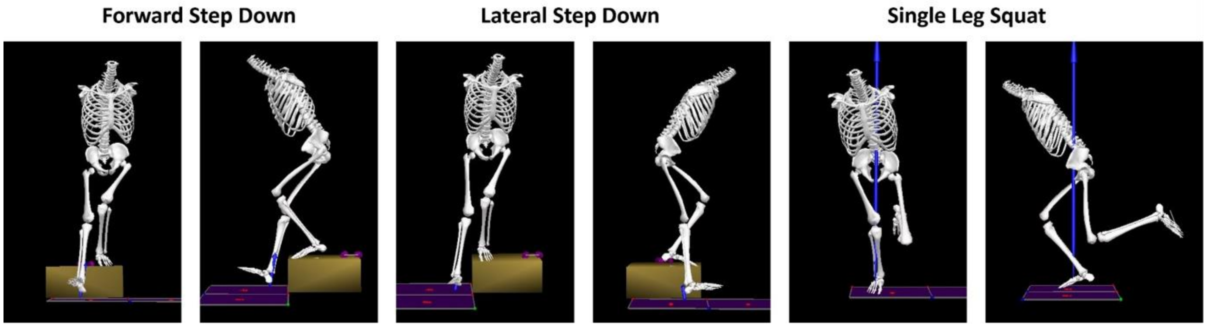

Figure 2.1 Depiction of Visual 3D model during each of the three tasks.

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 101 data points (100% of cycle) 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.

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. Descriptive data of peak angles and their timing were calculated to provide further context for the time-series.

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 2.2-4,). When performing the LSD, participants demonstrated increased pelvic tilt ($p=0.02$, 6-40%, Figure 4) and trunk flexion ($p=0.04$, 6-15%, Figure 5) when compared to the FSD. Participants also performed the FSD with greater knee abduction (Figure 6) 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 7). 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 ± 5.1cm), followed by the FSD (21.6 ± 1.3cm), and LSD (19.0 ± 1.0cm).

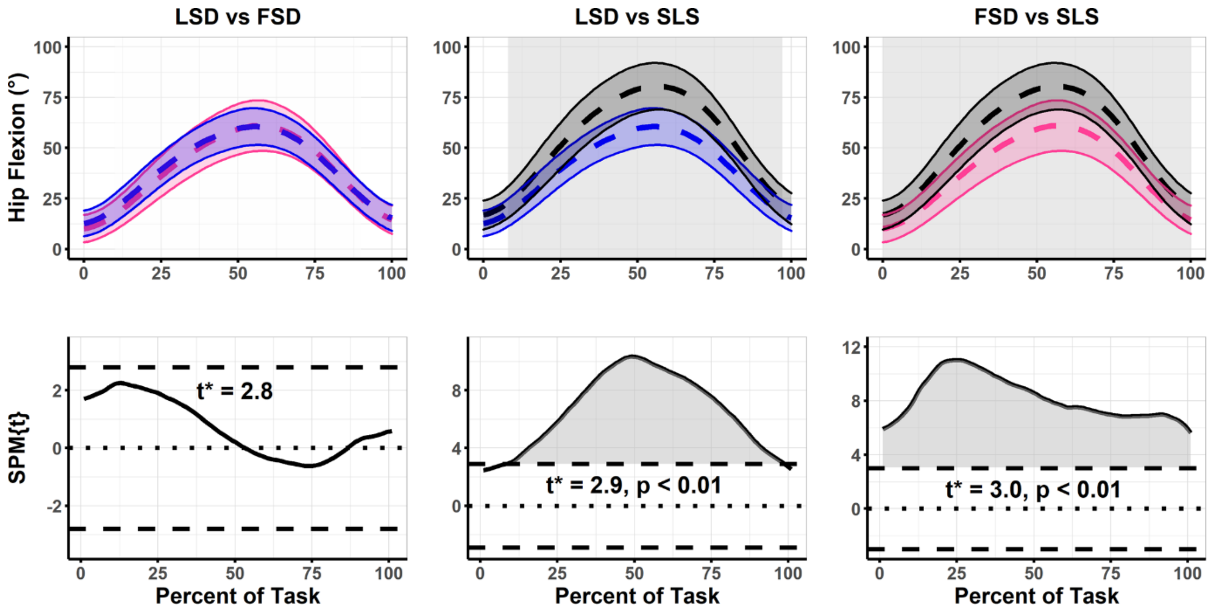

Figure 2.2 Kinematic waveforms for hip flexion. Blue = LSD, Pink = FSD, Black = SLS. Shaded areas indicate significant differences. Below: SPM t-tests, dashed lines indicate threshold for significant differences; shaded areas indicate where the threshold was exceeded.

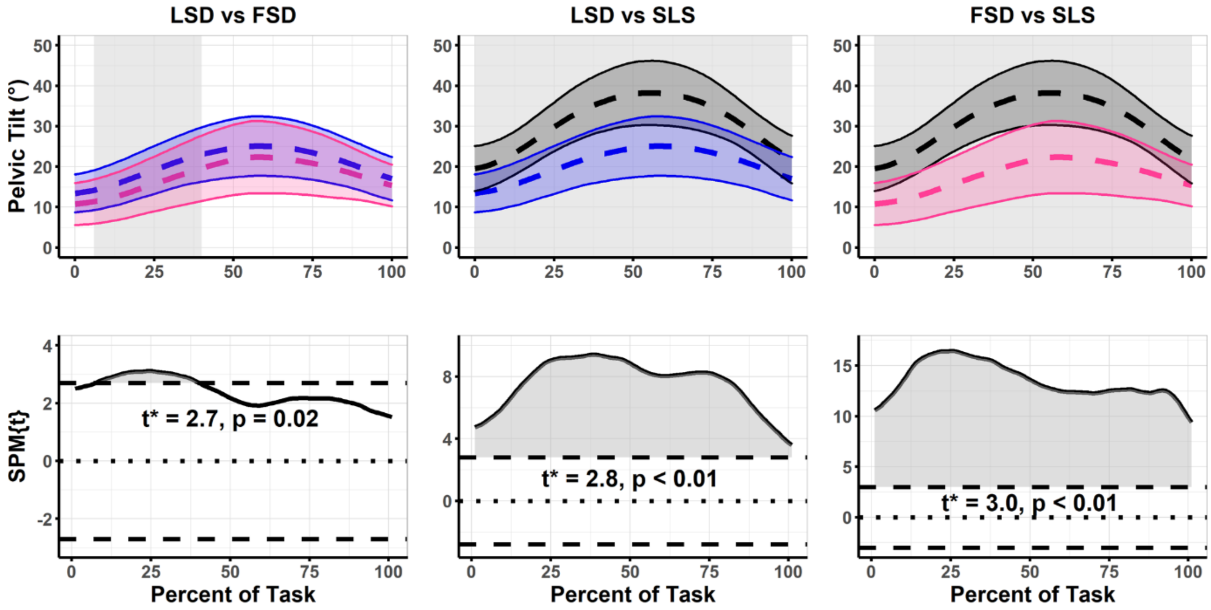

Figure 2. 3 Kinematic waveforms for pelvic tilt. Blue = LSD, Pink = FSD, Black = SLS. Shaded areas indicate significant differences. Below: SPM t-tests, dashed lines indicate threshold for significant differences; shaded areas indicate where the threshold was exceeded.

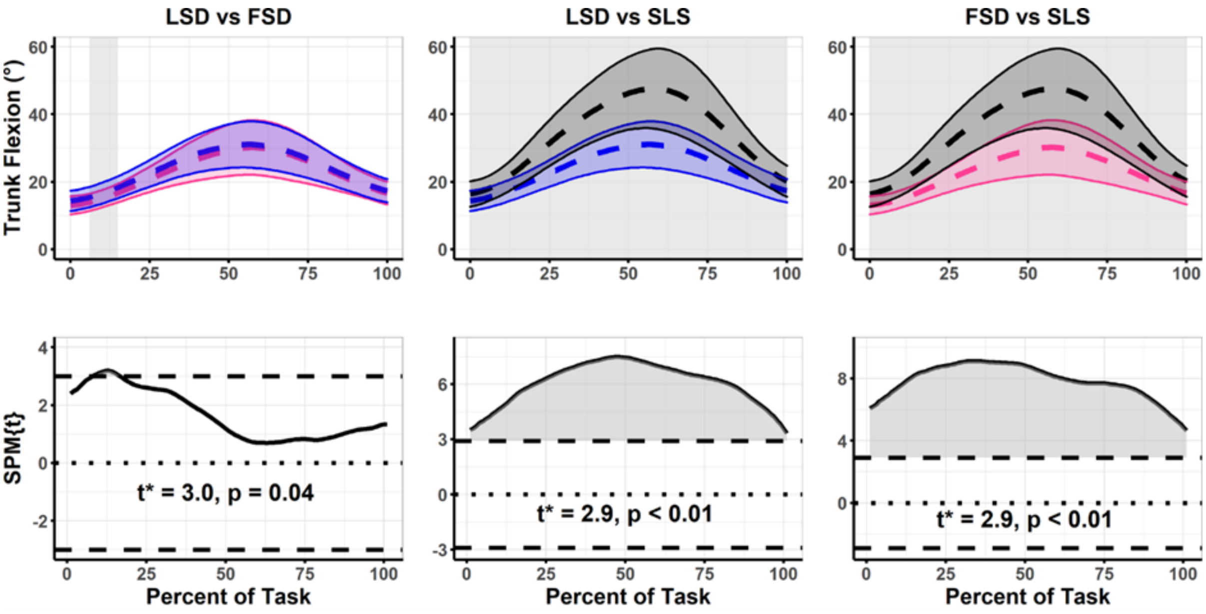

Figure 2.4 Kinematic waveforms for trunk flexion. Blue = LSD, Pink = FSD, Black = SLS. Shaded areas indicate significant differences. Below: SPM t-tests, dashed lines indicate threshold for significant differences; shaded areas indicate where the threshold was exceeded

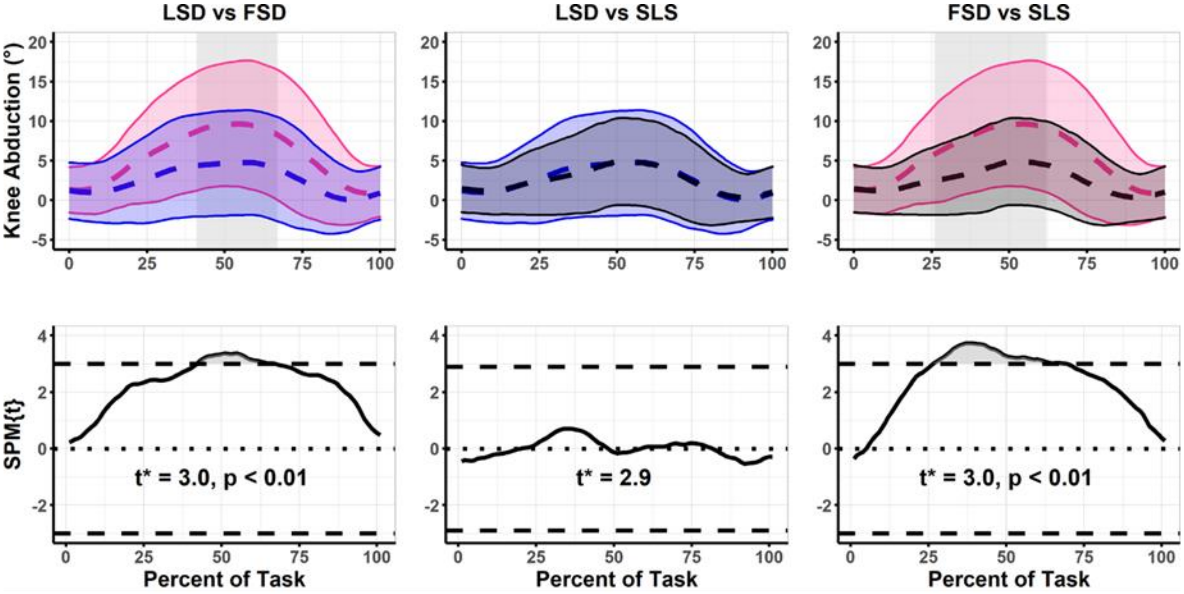

Figure 2.5 Kinematic waveforms for knee abduction. Blue = LSD, Pink = FSD, Black = SLS. Shaded areas indicate significant differences. Below: SPM t-tests, dashed lines indicate threshold for significant differences; shaded areas indicate where the threshold was exceeded

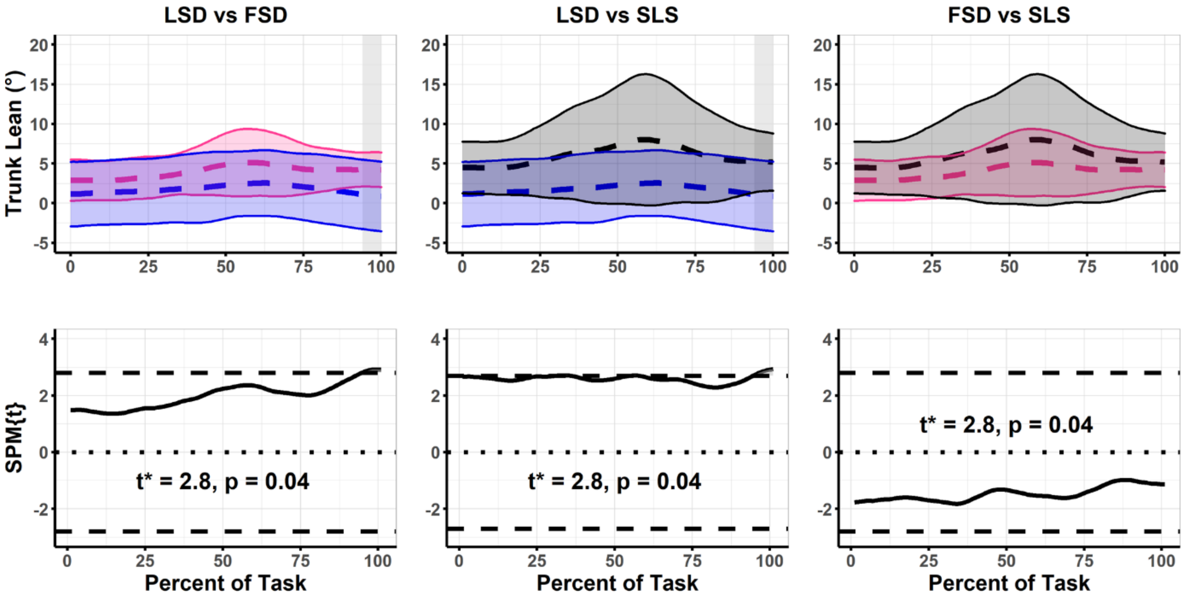

Figure 2.6 Kinematic waveforms for ipsilateral trunk lean. Blue = LSD, Pink = FSD, Black = SLS. Shaded areas indicate significant differences. Below: SPM t-tests, dashed lines indicate threshold for significant differences; shaded areas indicate where the threshold was exceeded

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. Each of these tasks were found to elicit differences in the kinematic waveforms and vertical COM displacements, indicating different task demands on the system. The hypothesis that the FSD would elicit less sagittal plane trunk, hip, and pelvic motion was supported (Figures 2.2-4). The SLS provoked the most sagittal plane motion as demonstrated by increased flexion at the trunk, pelvis, and hip, which resulted in greater vertical displacement of the COM compared to both the FSD and LSD. Furthermore, the hypothesis that the SLS would elicit the greatest magnitude of hip adduction and knee abduction was not supported. This hypothesis was rejected because during the FSD, knee abduction was greater than both the LSD and SLS (Figure 2.5) and no frontal plane differences were observed at the hip. The mean value for ipsilateral trunk lean was less through the duration of the LSD, but this only became significant toward the end of the task. Other kinematic waveforms in the frontal plane, such as hip adduction, and pelvic drop were not affected by the different demands of the three tasks.

Assessing the overall movement pattern revealed that performing the FSD resulted in greater knee abduction than the other two tasks from 26-62% of the movement. Interestingly, the greater vertical displacement of the COM during the SLS did not result in greater knee abduction. 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 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] However, the current study's population had increased hip flexion angles during the entire waveform of the SLS which 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 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.[32] Additionally, the increased sagittal plane demand and depth of squat during the SLS make it the best of the three tasks when training to increase jumping performance.[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. 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 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 2.6). 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 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 the 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.

Conclusion

The results of the current study indicate that subtle changes between the leg position and task demands during the SLS, FSD, and LSD resulted in different movement patterns between the tasks. When selecting a task to elicit lower extremity functional testing, the current study identified the FSD task may be best applied to movement screens that want to target excessive frontal plane knee motion. Whereas the SLS would be most useful for exercises that want to place demands on the muscles of the hip in the sagittal plane. The LSD task reduced frontal plane trunk motion relative to the other two tasks and may be best used to limit frontal plane knee torque during rehabilitation.

References

1. Ressman J, Grooten WJA, Rasmussen Barr E. Visual Assessment of Movement Quality in the Single Leg Squat Test: A Review and Meta-Analysis of Inter-Rater and Intrarater Reliability. *BMJ Open Sport Exerc Med*. 2019;*5(1).*

2. Rabin A, Portnoy S, Kozol Z. The Association Between Visual Assessment of Quality of Movement and Three-Dimensional Analysis of Pelvis, Hip, and Knee Kinematics During a Lateral Step Down Test. *Strength Cond J*. 2016; *30(11*): 3204-3211.

3. Park KM, Cynn HS, Choung SD. Musculoskeletal Predictors of Movement Quality for the Forward Step-down Test in Asymptomatic Women. *J Ortho Sports Phys Ther*. 2013;43(7):504-510.

4. Rabin A, Kozol Z. Measures of range of motion and strength among healthy women with differing quality of lower extremity movement during the lateral step-down test. *J Ortho Sports Phys Ther*. 2010;*40(12)*: 792-800.

5. Khuu A, Lewis CL. Position of the Non-Stance Leg During the Single Leg Squat Affects Females and Males Differently. *Hum Mov Sci*. 2019;67.

6. Lewis CL, Foch E, Luko MM, Loverro KL, Khuu A. Differences in lower extremity and trunk kinematics between single leg squat and step down tasks. *PLoS One*. 2015;*10(5).*

7. Werner DM, Davis RW, Hinton A, Price SK, Rowland JL, Barrios JA. Three-Dimensional Joint Kinematic and Two-Dimensional Quality of Movement Comparison Between Lateral and Forward Step-Downs. *Phys Ther Sport*. 2021;*52*:162-167.

8. Olivier B, Quinn SL, Benjamin N, Green AC, Chiu J, Wang W. Single-Leg Squat Delicacies-the Position of the Nonstance Limb is an Important Consideration. *J Sport Rehabil*. 2019;*28(4)*:318-324.

9. Khuu A, Foch E, Lewis CL. Not All Single Leg Squats Are Equal: a Biomechanical Comparison of Three Variations. *Int J Sports Phys Ther*. 2016;*11(2)*:201-211.

10. Chen S, Chang WD, Wu JY, Fong YC. Electromyographic Analysis of Hip and Knee Muscles During Specific Exercise Movements in Females With Patellofemoral Pain Syndrome an Observational Study. *Medicine*. 2018;*97(28).*

11. Kulas AS, Hortobágyi T, Devita P. Trunk Position Modulates Anterior Cruciate Ligament Forces and Strains During a Single-leg Squat. *Clin Biomech*. 2012;*27(1):*16-21.

12. 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.

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.

14. Hollman JH, Galardi CM, Lin IH, Voth BC, Whitmarsh CL. Frontal and transverse plane hip kinematics and gluteus maximus recruitment correlate with frontal plane knee kinematics during single-leg squat tests in women. *Clin Biomech*. 2014;*29(4):*468-474.

15. Claiborne TL, Armstrong CW, Gandhi V, Pincivero DM. Relationship Between Hip and Knee Strength and Knee Valgus During a Single Leg Squat. *J Appl Biomech*. 2006;*22*:41-50.

16. Pataky TC, Robinson MA, Vanrenterghem J. Vector Field Statistical Analysis of Kinematic and Force Trajectories. *J Biomech*. 2013;*46(14):*2394-2401.

17. Pataky TC, Robinson MA, Vanrenterghem J. Region-of-Interest Analyses of One Dimensional Biomechanical Trajectories: Bridging 0D and 1D Theory, Augmenting Statistical Power. *Peer J*. 2016;2016(11).

18. Pataky TC, Vanrenterghem J, Robinson MA. The Probability of False Positives in Zero-Dimensional Analyses of One-Dimensional Kinematic, Force and EMG Trajectories. *J Biomech*. 2016;49(9):1468-1476.

19. Pataky TC. Generalized N-dimensional Biomechanical Field Analysis Using Statistical Parametric Mapping. *J Biomech*. 2010;*43(10):*1976-1982.

20. Papi E, Bull AMJ, McGregor AH. Alteration of Movement Patterns In Low Back Pain Assessed by Statistical Parametric Mapping. *J Biomech*. 2020;*100*.

21. Carcia CR, Cacolice PA, McGeary S. Defining Lower Extremity Dominance: the Relationship Between Preferred Lower Extremity and two Functional Tasks. *Int J Sports Phys Ther*. 2019;*14(2):*188-191.

22. van Melick N, Meddeler BM, Hoogeboom TJ, Nijhuis-van der Sanden MWG, van Cingel REH. How to Determine Leg Dominance: The Agreement Between Self-reported and Observed Performance in Healthy Adults. *PLoS One*. 2017;*12(12).*

23. Pohl MB, Lloyd C, Ferber R. Can the Reliability of Three-Dimensional Running Kinematics be Improved Using Functional Joint Methodology? *Gait Posture*. 2010;*32(4):*559-563.

24. Lopes Ferreira C, Barton G, Delgado Borges L, dos Anjos Rabelo ND, Politti F, Garcia Lucareli PR. Step Down Tests are the Tasks That Most Differentiate the Kinematics of Women With Patellofemoral Pain Compared to Asymptomatic Controls. *Gait Posture*. 2019;*72*:129-134.

25. Baker R. Pelvic Angles: a Mathematically Rigorous Definition Which is Consistent With a Conventional Clinical Understanding of the Terms. *Gait Posture*. 2001;*13*:1-6.

26. Pataky TC. One-dimensional Statistical Parametric Mapping in Python. *Comput Methods Biomech Biomed Engin*. 2012;*15(3):*295-301.

27. Pataky TC, Vanrenterghem J, Robinson MA. Zero- vs. One-dimensional, Parametric vs. Non-parametric, and Confidence Interval vs. Hypothesis Testing Procedures in One-dimensional Biomechanical Trajectory Analysis. *J Biomech*. 2015;48(7):1277-1285.

28. Ugalde V, Brockman C, Bailowitz Z, Pollard CD. Single Leg Squat Test and Its Relationship to Dynamic KneeValgus and Injury Risk Screening. *PM and R*. 2015;*7(3):*229-235.

29. Crossley KM, Zhang WJ, Schache AG, Bryant A, Cowan SM. Performance on the Single-leg Squat Task Indicates Hip Abductor Muscle Function. *American Journal of Sports Medicine*. 2011;*39(4):*866-873.

30. Harris-Hayes M, Hillen TJ, Commean PK, et al. Hip Kinematics during Single Leg Tasks in People with and without Hip-Related Groin Pain and the Association among Kinematics, Hip Muscle Strength and Bony Morphology. *J Orthop Sports Phys Ther.* 2020;*50(5)*:243-251.

31. Hatfield GL, Charlton JM, Cochrane CK, et al. The Biomechanical Demands on the Hip During Progressive Stepping Tasks. *J Strength Cond*. 2016;*31(12):*3444-3453.

32. Clohisy JC, Knaus ER, Hunt DM, Lesher JM, Harris-Hayes M, Prather H. Clinical Presentation of Patients With Symptomatic Anterior Hip Impingement. In: *Clinical Orthopaedics and Related Research*. Vol 467. Springer New York; 2009:638-644.

33. Hartmann H, Wirth K, Klusemann M, et al. Influence of Squatting Depth on Jumping Performance. *J Strength Cond Res*. 2012;*26(12):*3243-3261.

34. McGovern RP, Martin RL, Christoforetti JJ, Kivlan BR. Evidence-Based Procedures for Performing the Sinigle Leg Squat and Step-Down Tests in Evaluation of Non-Arthritic Hip Pain: A Literature Review. *Int J Sports Phy Ther*. 2018;*13(3):*526-536.

35. da Costa GV, de Castro MP, Sanchotene CG, Ribeiro DC, de Brito Fontana H, Ruschel C. Relationship Between Passive Ankle Dorsiflexion Range, Dynamic Ankle Dorsiflexion Range and Lower Limb and Trunk Kinematics During the Single-leg Squat. *Gait Posture*. 2021;*86*:106-111.

36. Kluger D, Major MJ, Fatone S, Gard SA. The Effect of Trunk Flexion on Lower-Limb Kinetics of Able-bodied Gait. *Hum Mov Sci*. 2014;*33(1):*395-403.

37. Mitchell K, Porter M, Anderson L, et al. Differences in Lumbar Spine and Lower Extremity Kinematics in People With and Without Low Back Pain During a Step-up Task: A cross-sectional study. *BMC Musculoskelet Disord*. 2017;*18(1).*

38. Takacs J, Hunt MA. The Effect of Contralateral Pelvic Drop and Trunk Lean on Frontal Plane Knee Biomechanics During Single Limb Standing. *J Biomech*. 2012;*45(16):*2791-2796.

39. Pompeo KD, da Rocha ES, Morales AB, Klein KD, Vaz MA. Does Forward Step-down Task Frontal Kinematics Differ in Women With and Without Patellofemoral pain? A Cross-sectional Study. *Sport Sci Health*. Published online November 20, 2021.

40. Martonick NJP, Chun, Y, Krumpl L, Bailey J. Lower Extremity Kinematic Waveform Analysis During a Single Leg Drop Task – a Single Subject Approach. *J Sports Phys Ther.* In press.

41. Leardini A, Biagi F, Merlo A, Belvedere C, Benedetti MG. Multi-Segment Trunk Kinematics During Locomotion and Elementary Exercises. *Clin Biomech*. 2011;*26(6):*562-571.

Chapter 3:

Influence of Lateral Preference and Single Subject Analyses on Three Single Leg Movement Screens

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Significance of the Chapter

The first study of this dissertation demonstrated that the subtle differences between the tasks demands during the single leg squat (SLS), forward step down (FSD), and lateral step down (LSD) influenced the overall movement pattern required to complete the task. The design of the study considered only the participant’s self-identified most stable leg. Preliminary analyses of the first study indicated that there were minimal group differences when the preferred and non-preferred legs were considered. Conventional research also supports the idea that healthy individuals have symmetrical lower extremity movement. However, use of a group design to compare preferred and non-preferred legs may have obfuscated bilateral differences at the single subject level due to intraparticipant variability. The potential for asymmetrical movement patterns to occur at the single subject level is important because the assumption of symmetry may negatively impact rehabilitative protocols. Therefore, the second stage of this dissertation was used to expand on the findings of stage one by exploring the potential for bilateral differences to occur at the single subject level, and whether one task would best invoke asymmetries.

Abstract

Apparently healthy individuals are assumed to have symmetrical movement patterns during single leg weightbearing tasks such as the Forward Step Down (FSD), Lateral Step Down (LSD) and Single Leg Squat (SLS). The current evidence in support of symmetry has focused on group analyses, which may mask differences at the individual level. The primary purpose of this study was to examine the potential of bilateral differences to occur in apparently healthy individuals at the group and single subject level The secondary purpose of this study was to explore which tasks were more sensitive to asymmetries at trunk and lower extremities in the frontal or sagittal planes. Frontal and sagittal plane trunk, pelvis, hip, and knee kinematics of 23 healthy individuals were analyzed bilaterally with statistical parametric mapping (SPM). Participants identified task specific preferred and non-preferred legs. Dependent variables were analyzed using both group and single subject approaches to capture the potential of group masking. Minimal differences occurred at the group level when comparing preferred and non-preferred legs during the FSD, LSD, and SLS. Pelvic drop was greater on the non-preferred leg from 41-77% of the LSD (p=0.01). There were no other significant group findings for the LSD, FSD, or SLS. At the single subjects level, the largest percentage of participants with asymmetries occurred at the knee in the frontal plane (SLS = 78%, LSD = 71%, FSD = 70%). Sagittal plane asymmetries were most common at the pelvis during the FSD (FSD = 56%, SLS = 48%, LSD = 38%). Individual assessments were necessary for identifying asymmetrical movement patterns. Asymmetries should be considered by clinicians when using the uninjured limb as guide for rehabilitative goals. The LSD may best identify imbalances for pelvic drop.

Key Words: Bilateral differences, Rehabilitation, Movement Screens

Introduction

Lower extremity movement symmetry is often established as a rehabilitation goal with patients who have injuries that limit movement on one side of the body.[1] During rehabilitation of the injured leg, the contralateral leg may be used as the benchmark for rehabilitation goals and return to play protocols. The selection of the contralateral limb as the standard point of reference is supported by the idea that healthy individuals display symmetrical lower extremity movement patterns between legs.[2–4] However, the assumption of symmetry could lead to inadequate treatment goals if asymmetries were present prior to the injury.

Investigations of movement symmetry have primarily focused on group mean data, without consideration for single subject analyses.[2,3,5] Although group analyses may provide information on the probability that the average performance within the group will occur in a larger population; different movement strategies can affect the statistical outcomes.[6] The effect of different movement strategies may be of particular importance when determining the potential for bilateral asymmetries.[7,8] For example, group differences may be masked in situations when some individuals have increased values on the "dominant" side and others have greater values on the "non-dominant" side. In which case, the means would indicate that there is no difference between sides. This is one reason why researchers have contended that single subject post hoc analyses should be reported in addition to group analysis when making bilateral comparisons.[6,8,9]

Selection of the appropriate leg for dichotomization is another challenge when investigating bilateral differences at a group level. Individuals will often develop a tendency for performing movement patterns with an approach that favors one side of the body. The term "lateral preference" (often termed leg dominance) has been used to describe the development of a specific arm or leg to perform a given task.[10,11] A common method for determining leg dominance is to identify the leg used to kick a ball;[3] even though, lateral preference has been shown to be task specific.[12–14] Thus, the selection of the kicking leg to stratify the lower extremities during single leg tasks may be inappropriate and limit research findings. Lateral preferences should therefore be assessed on a task-by-task basis.

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.[15,16] While the kinematic profiles of the FSD, SLS, and LSD have been compared,[17–19] these investigations have only examined differences between the tasks using one side of the body, or the dominant leg. Current evidence is limited for whether one of the aforementioned movements better invokes asymmetries when imbalances are present. This information may be valuable when assessing populations that are thought to lack movement symmetry. For example, imbalances in trunk and lower extremity frontal plane kinematics often follow anterior cruciate ligament reconstruction (ACLR),[20,21] Following hamstring injury, sprinters may present with sagittal plane asymmetries at the pelvis, hip, and knee.[22,23] Therefore, the identification of a single leg movement that better invokes asymmetries in the frontal or sagittal planes would aid clinicians when selecting the appropriate task for individuals at risk of imbalances.

The primary purpose of this study was to examine the potential of bilateral differences to occur in apparently healthy individuals at the group and single subject level. As lateral preference has been shown to be task specific, participants identified their preferred (perceived as most stable) and non-preferred legs for each task. It was hypothesized that frontal plane asymmetries would result in increased frontal plane motion on the non-preferred legs, and sagittal plane asymmetries would have a greater magnitude on the preferred side. A secondary hypothesis was that a single subject approach would reveal bilateral differences that would otherwise be masked by the group analysis. The secondary purpose of this study was to explore which tasks were more sensitive to asymmetries at trunk and lower extremities in the frontal or sagittal planes. It was hypothesized that the SLS would invoke more asymmetries in the sagittal plane at the hip and knee due to squat depth not being limited.

Methods

Participants

Twenty-three participants (11 female, 24.5 ± 4.9 years, 174.2 ± 6.7 cm, 67.7 ± 15.5 kg) volunteered for this within-subjects, repeated-measures study design. Only 21 participants (11 female, 22.7 ± 3.03 years, 171.5 ± 6.5 cm, 66.3 ± 10.2 kg) were used in the

LSD analyses, due to lost or missing data. 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 a sign of mobility and stability. 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.

Procedures

Prior to collecting data, the participants were asked to perform each of the three tasks (FSD, SLS, LSD) bilaterally 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 screen. Lateral preference (i.e., limb dominance) for this study was task specific creating the possibility of differences across tasks per participant.[10,11] Participants were then fitted with a custom cluster-based reflective marker set that defined the trunk, pelvis, thighs, and shanks. 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 participants hands came off their waist, they performed the trial in a jerky or non-continuous manner, or lost balance. Participants completed all trials of one task prior to changing tasks. Task order was randomized across participants to account for order effect.

The SLS was performed to the depth the participant could achieve while still performing one continuous motion. The non-weightbearing leg was placed in a neutral hip position with the knee flexed to approximately 90°. 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 20cm 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.[19,24] 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.[19]

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.[25] 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 weightbearing 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.[17,26] Kinematic time-series were interpolated to 101 data points (100% of cycle) for the 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.[27] The end of the task was defined as the point when hip flexion returned to that starting value.

Statistical Analysis

All SPM analyses were conducted in MATLAB using an open-source software package spm1D 0.4.[28] Paired *t*-tests were performed between preferred and non-preferred legs for group (i.e., preferred vs. non-preferred) and single subject analyses. The significance level for all statistical tests was set a priori to an alpha of 0.05. An alpha correction was not deemed appropriate because the procedure requires independence across the tests which is not the case with time-series data.[29] Additionally, SPM analyses have been shown to reduce type I error associated with kinematic data.[29,30] The null hypothesis was rejected if the computed *t*-value exceeded the critical threshold. For group data, the participant's mean values of the five trials, for both the preferred and non-preferred legs, were calculated for each task and used for analysis. For the single subject analyses, the five trials were compared between the two legs for each task.[31] When the participant's statistical difference between legs crossed the critical threshold, the timing of this cross from 0-100% of the movement was recorded. If any portion of the task reached statistical difference, the participant was classified as containing an asymmetry and reported as a percentage of the population.

Results

Contralateral pelvic drop was increased on the non-preferred leg from 41-77% of the movement ($p = 0.01$, Figure 3.1) for the LSD group analysis. No other significant differences were found for the LSD group analysis. There were no significant bilateral differences recorded for the FSD and SLS throughout the entire cycle for the group analyses.

For the single subject analyses, the number of participants with significant differences were task and variable dependent. The largest percentage of asymmetries occurred at the knee in the frontal plane, with the SLS having the highest percentage of participants with significant findings (78%, Figure 3.2). The SLS also identified the highest percentage of participants with bilateral differences for knee flexion (48%, Figure 3.3). During the FSD, participants demonstrated the highest percentage of asymmetries for hip flexion (43%, Figure 3.4) and anterior pelvic tilt (56%, Figure 3.5). Asymmetries for ipsilateral trunk lean were highest during the LSD (57%, Figure 3.6); however, the LSD had the lowest percentage of participants with sagittal plane asymmetries at the hip (24%, Figure 3.4), pelvis (38%, Figure 5), and trunk (29%, Figure 3.7). The LSD was also shown to have the lowest percentage of bilateral differences for hip adduction (57%, Figure 3.8).

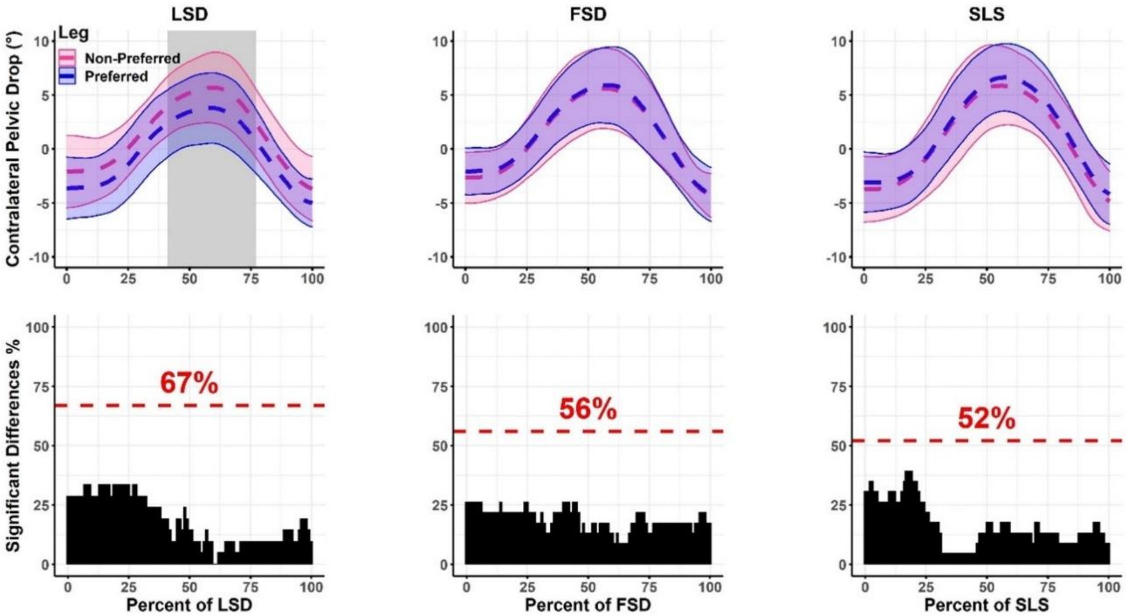

Figure 3.1 Top row plots display time series for group comparisons of pelvic drop with shaded area indicating a significant difference between groups. Bottom row displays results of single subject analyses. Red dashed line indicates the overall percentage of individuals with a significant difference. Black bars represent the percentage of participants with a significant difference at each percentage of the task.

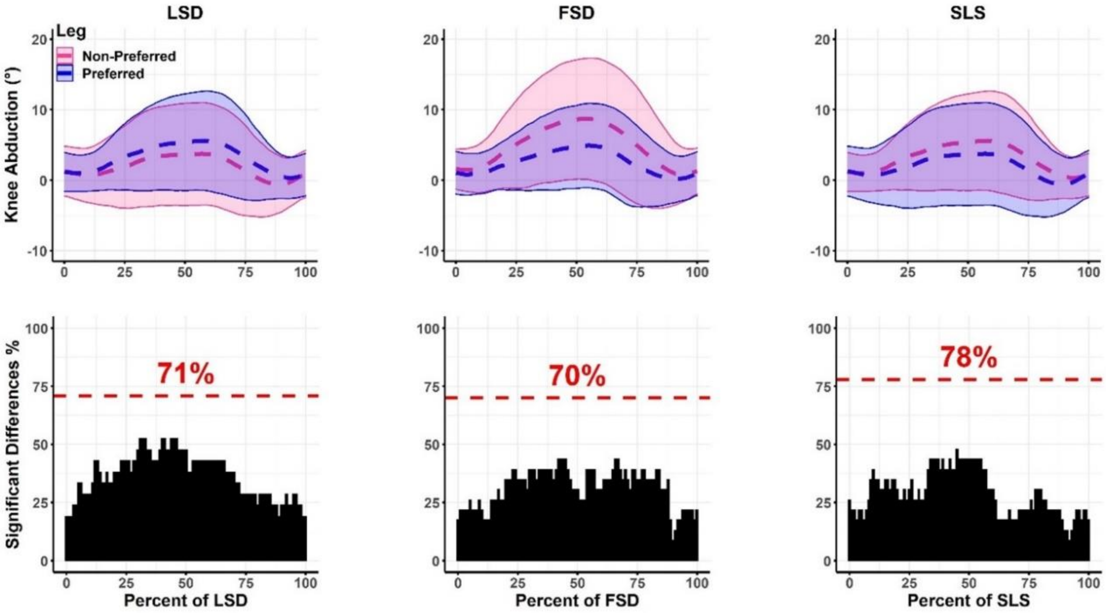

Figure 3.2 Top row plots display time series for group comparisons of knee abduction. Bottom row displays results of single subject analyses. Red dashed line indicates the overall percentage of individuals with a significant difference. Black bars represent the percentage of participants with a significant difference at each percentage of the task.

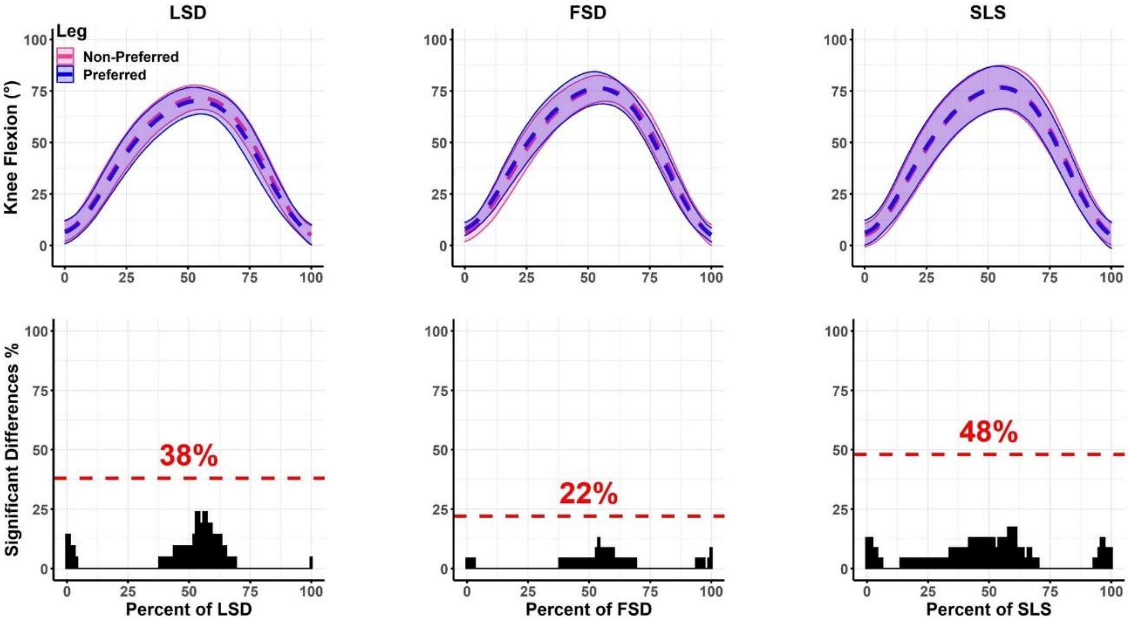

Figure 3.4 Top row plots display time series for group comparisons of knee flexion. Bottom row displays results of single subject analyses. Red dashed line indicates the overall percentage of individuals with a significant difference. Black bars represent the percentage of participants with a significant difference at each percentage of the task.

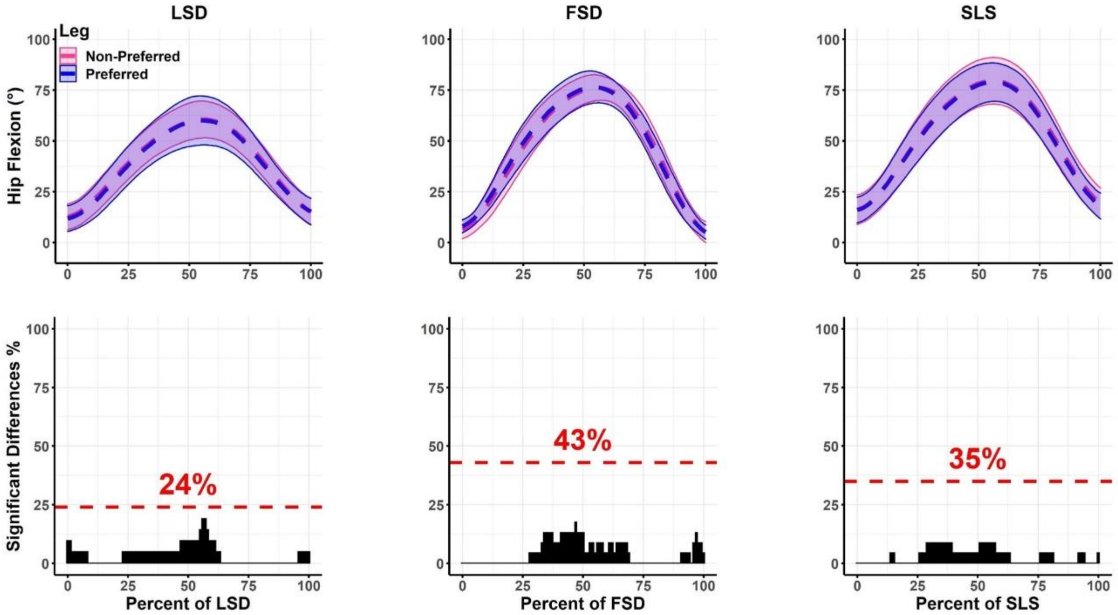

Figure 3.3 Top row plots display time series for group comparisons of hip flexion. Bottom row displays results of single subject analyses. Red dashed line indicates the overall percentage of individuals with a significant difference. Black bars represent the percentage of participants with a significant difference at each percentage of the task.

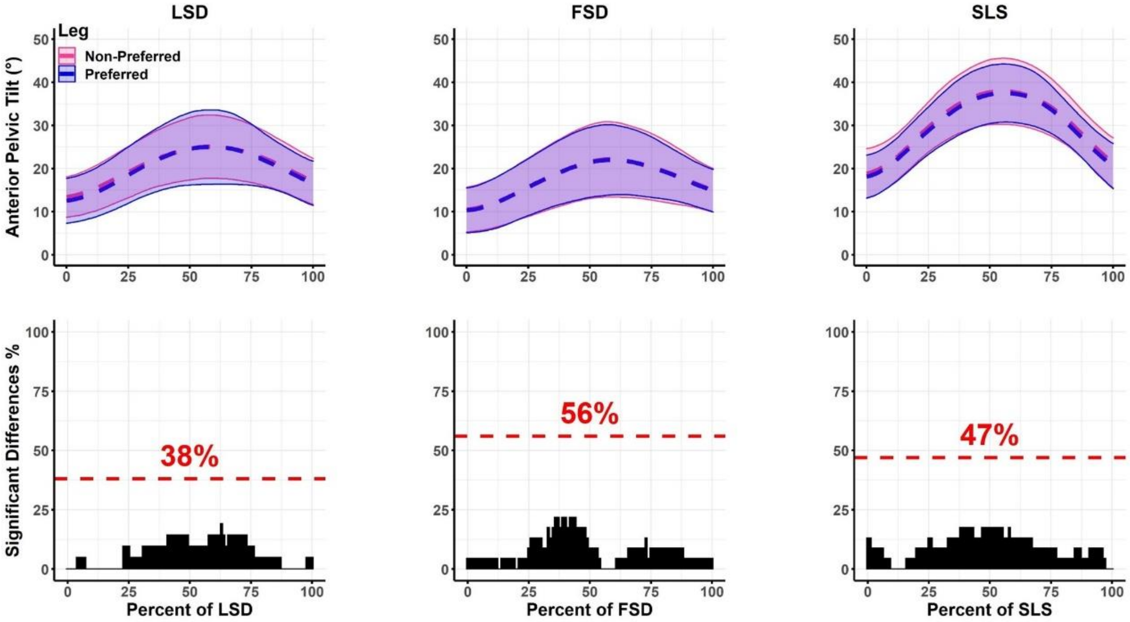

Figure 3.6 Top row plots display time series for group comparisons for pelvic tilt. Bottom row displays results of single subject analyses. Red dashed line indicates the overall percentage of individuals with a significant difference. Black bars represent the percentage of participants with a significant difference at each percentage of the task.

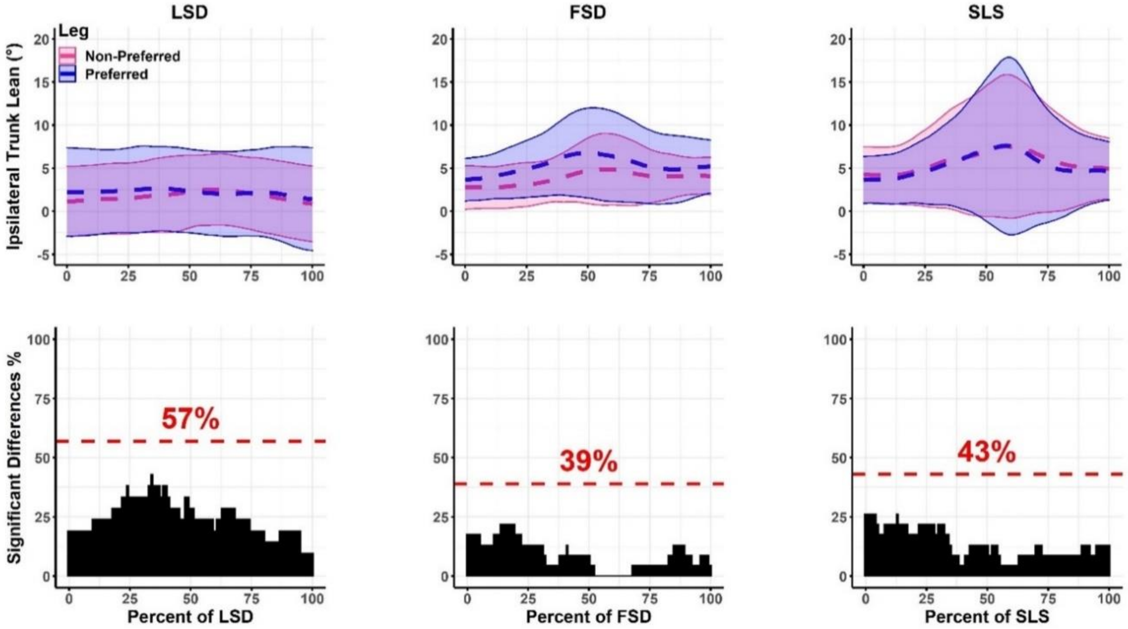

Figure 3.5 Top row plots display time series for group comparisons for ipsilateral trunk lean. Bottom row displays results of single subject analyses. Red dashed line indicates the overall percentage of individuals with a significant difference. Black bars represent the percentage of participants with a significant difference at each percentage of the task.

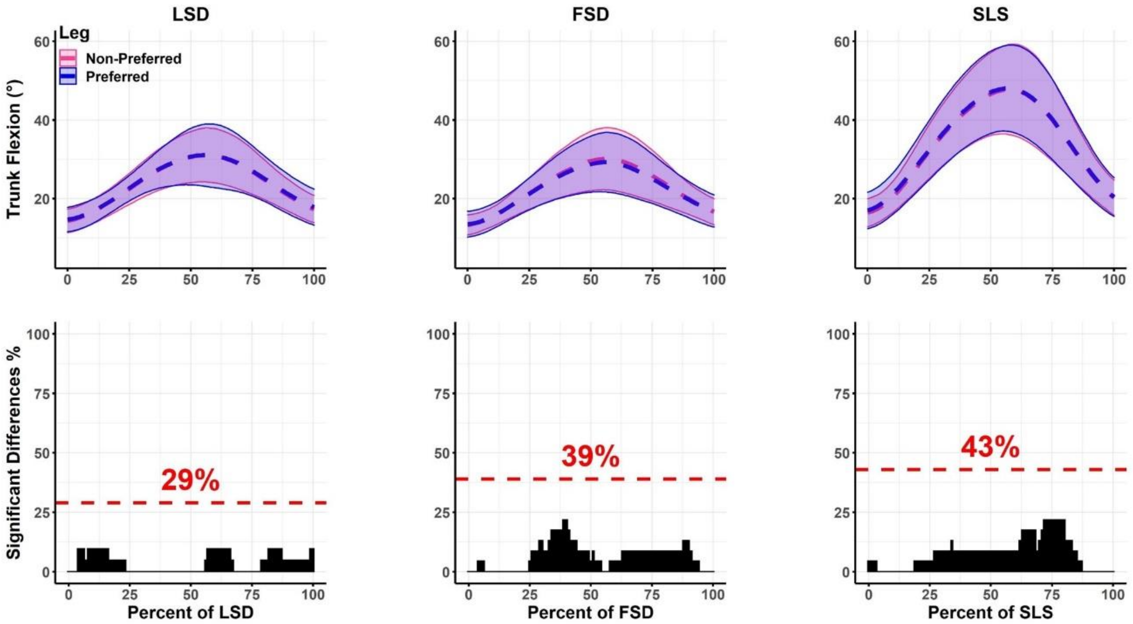

Figure 3.7 Top row plots display time series for group comparisons for trunk flexion. Bottom row displays results of single subject analyses. Red dashed line indicates the overall percentage of individuals with a significant difference. Black bars represent the percentage of participants with a significant difference at each percentage of the task.

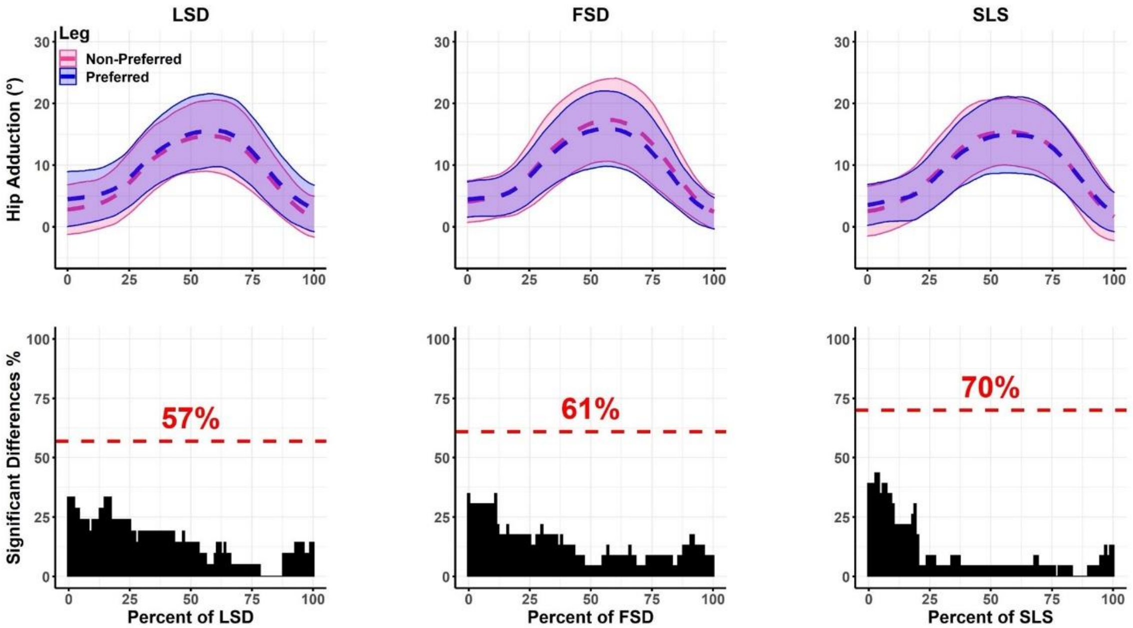

Figure 3.8 Top row plots display time series for group comparisons for hip adduction. Bottom row displays results of single subject analyses. Red dashed line indicates the overall percentage of individuals with a significant difference. Black bars represent the percentage of participants with a significant difference at each percentage of the task.

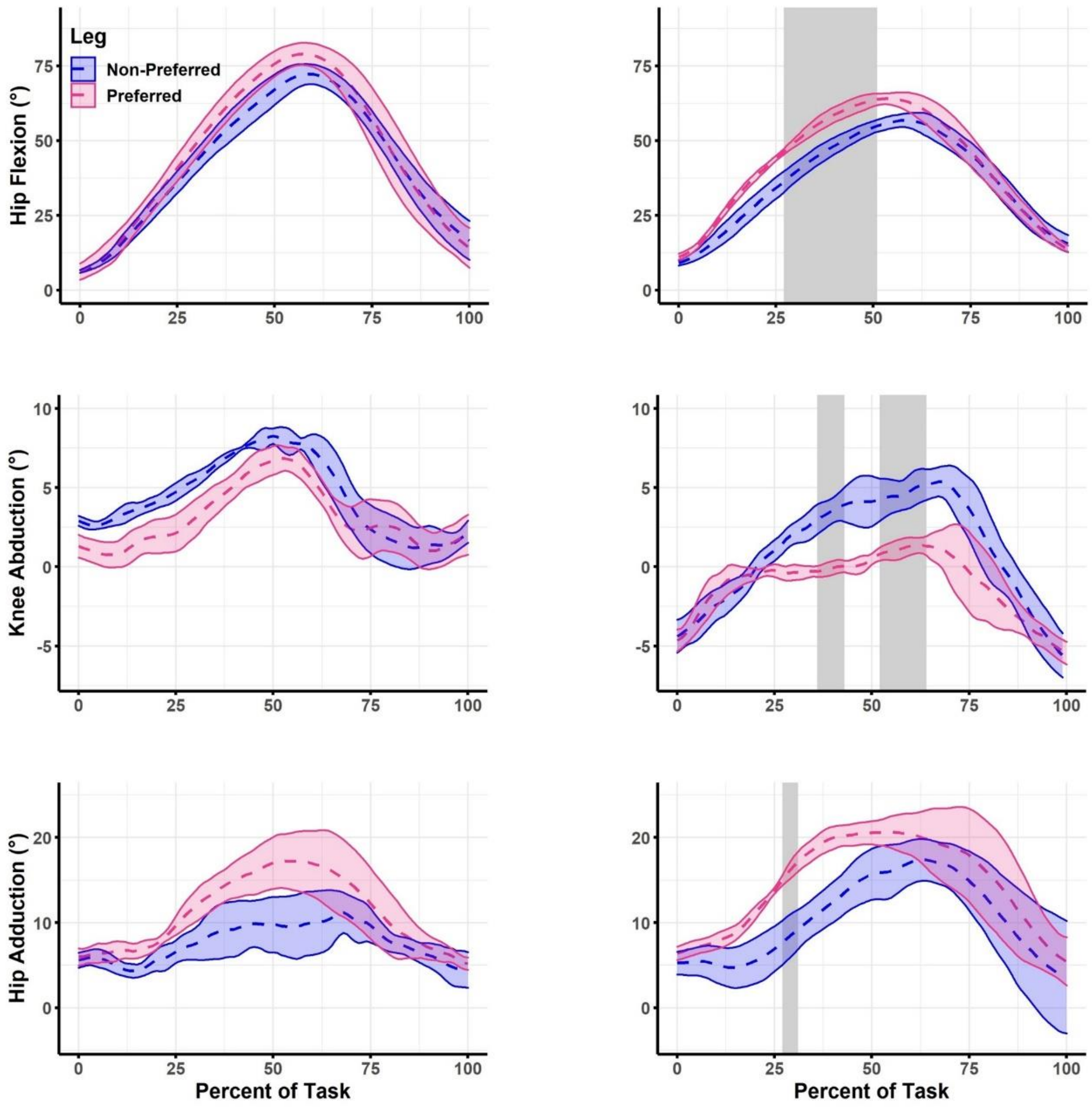

Figure 3.9 Examples of single subject analyses. Shaded regions indicate statistically significant differences p < 0.05.

Discussion

The primary purpose of this study was to examine the potential of bilateral differences to occur in apparently healthy individuals at the group and single subject level. At the group level there were minimal kinematic bilateral differences in the frontal and sagittal planes between the preferred and non-preferred legs across the LSD, FSD, and SLS. The hypothesis that sagittal plane asymmetries would demonstrate greater motion on the preferred leg was rejected at the group level due to a lack of significant findings. However, the hypothesis that frontal plane asymmetries would result in increased frontal plane motion on the non-preferred leg was partially accepted due to significant findings at the pelvis during the LSD (Figure 3.1). As excessive pelvic drop during the LSD is considered a "faulty" movement pattern and a sign of instability,[32] the LSD may be the best task for identifying imbalances for pelvic stability at the group level. At the single subject level, 67% of the participants were shown to have bilateral differences during the LSD. Although group findings were statistically significant for difference between the preferred and non-preferred legs, the timing of the group difference contrasted what was presented at the single cases level. Timing for the statistical difference between group data occurred from 41-77% of the movement (Figure 3.1). In contrast, the single subject analysis indicated that during the first 30% of the movement there was the largest concentration of significant differences among individuals with statistical asymmetries (Figure 3.1). This inconsistency between the timing of significant differences at the group and single subject level provides evidence that averaged movement patterns incorrectly represent bilateral differences of individuals.

Prior investigations using a single subject design have also observed that group mean data did not represent individual movement patterns.[6,33,34] Thus, there is a demand to combine group and single subject analyses when attempting to identify bilateral differences while accounting for participant variability. For instance, the lack of a single subject analysis may have limited the findings of a recent study [2] that used an SPM analysis to investigate bilateral kinematic symmetry during a SLS. No group kinematic differences at the pelvis, hip, or knee, in the frontal and sagittal planes were found among a population of healthy individuals who performed the SLS. The authors [2] concluded that symmetry between legs is predominant in healthy individuals. A similar conclusion could be made based on the group findings from the current study. However, bilateral differences were prevalent among the current study's population when individual assessments were performed. For example, 71% of participants had bilateral differences in frontal plane knee motion during the LSD, 70% during the FSD, and 78% during the SLS (Figure 3.2). Additionally, frontal plane hip motion was significantly different between the two legs in 57% participants during the LSD, 61% of participants during the FSD, and 70% of participants during the SLS (Figure 3.8). The obfuscation of individual bilateral differences at the group level is not novel to our study.[7,35,36] Thus, the hypothesis that a single subjects approach would elicit greater bilateral differences across tasks was accepted.

The minimal differences at the group level may be explained by dissimilar movement patterns between the preferred and non-preferred legs of individual participants in this study. Specifically, differences in the mean data may have been canceled out by some participants having greater magnitudes on the preferred leg and others on the non-preferred leg. This was made evident by the single subject approach for frontal plane hip motion. An equal number of participants with bilateral differences had increased hip adduction on the non-preferred leg as those that did on the preferred leg for each of the three tasks. A similar observation was made for frontal plane knee motion during the FSD. Of the 70% of participants that had a significant difference during the FSD, 50% of those participants had increased knee abduction on the preferred leg. The exception to this inter-participant variability occurred for frontal plane pelvis kinematics during the LSD. During the LSD, 85% (12/14) of the participants with bilateral differences demonstrated increased contralateral pelvic drop on the non-preferred leg. It is likely that the similar movement pattern (i.e., increased pelvic drop) on the non-preferred legs is what resulted in the significant group finding. Overall, lateral preference was not indicative of whether a participant would have increased or decreased motion on the preferred or non-preferred side.

The secondary purpose of this study was to explore which tasks were more sensitive to asymmetries at trunk and lower extremities in the frontal or sagittal planes. Due to the limitation of the group analysis to correctly detect asymmetries, it was necessary to compare tasks at the single subject level. As the SLS had the highest percentage of participants with bilateral differences for knee flexion (Figure 3.3) and trunk flexion (Figure 3.7), the hypothesis that the SLS would invoke more asymmetries in the sagittal plane was partially accepted. The FSD was also shown to have a greater percentage of participants with sagittal plane asymmetries for hip flexion (Figure 3.4), and pelvic tilt (Figure 3.5). It appears that the FSD and SLS may be more sensitive to sagittal plane asymmetries than the LSD. For hip flexion, pelvic tilt, and trunk flexion, the LSD had the lowest percentage of asymmetries (Figures 3.4, 3.5, 3.7). Positioning of the non-stance leg in the anterior (FSD) and posterior (SLS) position likely influenced sagittal plane positioning of the center of mass (COM).[18,37] Whereas the placement of the leg under the COM during the LSD may have limited the task demand of mitigating COM translation in sagittal plane and resulted in fewer asymmetries. The identification of asymmetries in the sagittal plane may be of particular importance in the examination of sprinters who have or may go on to suffer hamstring strains.[22,23] Sprinters with prior hamstring strains have been shown to have increased hip flexion and anterior pelvic tilt, as well as decreased knee flexion, on the injured leg through the stance phase of sprinting.[22,23] Therefore, the FSD or SLS may be valuable tools in the clinical assessment of individuals who have suffered or are at risk of hamstring strains.

Kinematic asymmetries in frontal plane knee motion often occur following injuries such as ACLR.[20,21] As each of the three tasks found bilateral differences in 70% or more of the participants in this study (Figure 3.2), clinicians may consider the effectiveness of the LSD, FSD, and SLS to detect frontal plane knee asymmetries when assessing the movement symmetry of patients who have occurred ACLR. The LSD demonstrated the highest percentage of participants with pelvic drop asymmetries (67%, Figure 3.1) and ipsilateral trunk flexion (57%, Figure 3.6). Thus, it may be well suited when assessing pelvic and trunk imbalances in athletes at risk of recurrent ACLR due to the population's propensity toward asymmetry for these variables.[38] Although clinicians can use the SLS, FSD, and LSD to identify asymmetrical movement, it should be noted that the return to symmetry may not be an adequate rehabilitation goal if the uninjured leg displays movement mechanics associated with a lack of stability or strength. Additionally, a battery of single leg movement tasks may be appropriate to identify asymmetries at different joints or segments.

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 at the group level. Next, kinematic trajectories are subject to error from marker placement, specifically in the frontal and transverse planes.[39,40] However, it has been demonstrated that errors in marker placement can be limited by having a single practitioner apply the reflective markers.[41] For this reason, all pelvis, hip, and knee markers were applied by the same researcher. Lastly, the single subjects 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 shown to have a range of power from 0.5-0.75 for a sample size of five.[42] Thus, differences may have occurred in the single case analyses that did not reach statistical significance due to a lack of power (Figure 3.9). Additionally, significant findings may have also presented with more or greater statistically significant differences between the two legs. Future analyses looking at differences greater than 5º may want to consider at least 7 trials to achieve a power of 0.8.[42]

Conclusion

In conclusion, the current study found that there were minimal differences at the group level when comparing preferred and non-preferred legs during the FSD, LSD, and SLS. Single subject analyses were necessary to elucidate when bilateral differences occurred. It appears that symmetry is not common in healthy individuals, and the presences of asymmetries prior to injury should be considered by clinicians. The FSD and SLS are appropriate tasks for identifying sagittal plane imbalances, while the LSD invokes more asymmetrical movement patterns at the pelvis and trunk in the frontal plane.

References

1. Benjaminse A, Holden S, Myer GD. ACL rupture is a single leg injury but a double leg problem: Too much focus on “symmetry” alone and that’s not enough! *Br J Sports Med*. 2018;52(16):1029-1030.

2. Ksoll H, Cotic M, Schmalzl K, et al. Movement coordination during functional single-leg squat tests in healthy, recreational athletes. Published online 2022.

3. 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*. 2017;27(11):1328-1336.

4. Brown AM, Zifchock RA, Hillstrom HJ. The effects of limb dominance and fatigue on running biomechanics. *Gait Posture*. 2014;39(3):915-919.

5. 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.

6. Dufek JS, Bates BT, Stergiou N, James CR. Interactive effects between group and single-subject response patterns. *Hum Mov Sci*. 1995;14:301-323.

7. Schot PK, Bates BT, Dufek JS. Bilateral performance symmetry during drop landing: a kinetic analysis. *Med Sci Sports Exerc*. 1994;26(9):1153-1159.

8. Flanagan SP, Salem GJ. Bilateral differences in the net Joint Torques During the Squat Exercise. *J Strength Cond Res*. 2007;21(4):1220-1226.

9. Schot PK, Bates BT, Dufek JS. Bilateral performance symmetry during drop landing: a kinetic analysis. *Med Sci Sports Exerc*. 1994;26(9):1153-1159.

10. Carpes FP, Mota CB, Faria IE. On the bilateral asymmetry during running and cycling - A review considering leg preference. *Physical Therapy in Sport*. 2010;11(4):136-142.

11. McGrath TM, Waddington G, Scarvell JM, et al. The effect of limb dominance on lower limb functional performance – a systematic review. *J Sports Sci*. 2016;34(4):289-302.

12. Carcia CR, Cacolice PA, McGeary S. Defining Lower Extremity Dominance: the Relationship Between Preferred Lower Extremity and two Functional Tasks. *Int J Sports Phys Ther*. 2019;14(2):188-191.

13. Velotta J, Weyer J, Ramirez A, Winstead J, Bahamonde R. Relationship between leg dominance and type of task. *Biomechanics in Sports* . 2011;11:1035-1038.

14. van Melick N, Meddeler BM, Hoogeboom TJ, Nijhuis-van der Sanden MWG, van Cingel REH. How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults. *PLoS One*. 2017;12(12).

15. Rabin A, Kozol Z. Measures of range of motion and strength among healthy women with differing quality of lower extremity movement during the lateral step-down test. *Journal of Orthopaedic and Sports Physical Therapy*. 2010;40(12):792-800.

16. Ressman J, Grooten WJA, Rasmussen Barr E. Visual assessment of movement quality in the single leg squat test: A review and meta-analysis of inter-rater and intrarater reliability. *BMJ Open Sport Exerc Med*. 2019;5(1).

17. Lewis CL, Foch E, Luko MM, Loverro KL, Khuu A. Differences in lower extremity and trunk kinematics between single leg squat and step down tasks. *PLoS One*. 2015;10(5).

18. Werner DM, Davis RW, Hinton A, Price SK, Rowland JL, Barrios JA. Three-dimensional joint kinematic and two-dimensional quality of movement comparison between lateral and forward step-downs. *Physical Therapy in Sport*. 2021;52:162-167.

19. Lopes Ferreira C, Barton G, Delgado Borges L, dos Anjos Rabelo ND, Politti F, Garcia Lucareli PR. Step down tests are the tasks that most differentiate the kinematics of women with patellofemoral pain compared to asymptomatic controls. *Gait Posture*. 2019;72:129-134.

20. Hall MP, Paik RS, Ware AJ, Mohr KJ, Limpisvasti O. Neuromuscular evaluation with single-leg squat test at 6 months after anterior cruciate ligament reconstruction. *Orthop J Sports Med*. 2015;3(3).

21. Hughes G, Musco P, Caine S, Howe L. Lower limb asymmetry after anterior cruciate ligament reconstruction in adolescent athletes: A systematic review and meta-analysis. *J Athl Train*. 2020;55(8):811-825.

22. Ciacci S, di Michele R, Fantozzi S, Merni F. Assessment of Kinematic Asymmetry for Reduction of Hamstring Injury Risk Injury Prevention. *Int J Athl Ther Train.* Vol 18; 2013.

23. Daly C, Mccarthy Persson U, Twycross-Lewis R, Woledge RC, Morrissey D. The biomechanics of running in athletes with previous hamstring injury: A case-control study. *Scand J Med Sci Sports*. 2016;26(4):413-420. doi:10.1111/sms.12464

24. Park KM, Cynn HS, Choung SD. Musculoskeletal Predictors of Movement Quality for the Forward Step-down Test in Asymptomatic Women. *Journal of Orthopedic and Sports Physical Therapy*. 2013;43(7):504-510.

25. Baker R. Pelvic angles: a mathematically rigorous definition which is consistent with a conventional clinical understanding of the terms. *Gait Posture*. 2001;13:1-6.

26. Khuu A, Foch E, Lewis CL. Not All Single Leg Squats Are Equal: a Biomechanical Comparison of Three Variations. *Int J Sports Phys Ther*. 2016;11(2):201-211.

27. Lake JP, McMahon JJ. Within-subject consistency of unimodal and bimodal force application during the countermovement jump. *Sports*. 2018;6(4).

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

29. Houston A, Fong DTP, Bennett AN, Walters V, Barker-Davies RM. Biomechanical differences between military patients with patellar tendinopathy and asymptomatic controls during single-leg squatting and gait – A statistical parametric mapping study. *Clin Biomech*. 2021;90:105514.

30. Pataky TC. rft1d: Smooth one-dimensional random field upcrossing probabilities in Python. *J Stat Softw*. 2016;71.

31. Bates BT, Dufek JS, Davis HP. The effect of trial size on statistical power. *Med Sci Sports Exerc*. 1992;24(9):1059-1065.

32. Mostaed MF, Werner DM, Barrios JA. 2D and 3D Kinematics During Lateral Step-Down Testing In Individuals With Anterior Cruciate Ligament Reconstruction. *Int J Sports Phys Ther*. 2018;13(1):77-85.

33. Straker R, Exell TA, Farana R, Hamill J, Irwin G. Biomechanical responses to landing strategies of female artistic gymnasts. *Eur J Sport Sci*. Published online 2021.

34. Nordin AD, Dufek JS, James CR, Bates BT. Classifying performer strategies in drop landing activities. *J Sports Sci*. 2017;35(18):1858-1863.

35. Bartlett R, Wheat J, Robins M. Is movement variability important for sports biomechanists? *Sports Biomech*. 2007;6(2):224-243.

36. Scholes CJ, McDonald MD, Parker AW. Single-subject analysis reveals variation in knee mechanics during step landing. *J Biomech*. 2012;45(12):2074-2078.

37. Olivier B, Quinn SL, Benjamin N, Green AC, Chiu J, Wang W. Single-leg squat delicacies-the position of the nonstance limb is an important consideration. *J Sport Rehabil*. 2019;28(4):318-324.

38. King E, Richter C, Daniels KAJ, et al. Biomechanical but Not Strength or Performance Measures Differentiate Male Athletes Who Experience ACL Reinjury on Return to Level 1 Sports. *American Journal of Sports Medicine*. 2021;49(4):918-927.

39. Alenezi F, Herrington L, Jones P, Jones R. How reliable are lower limb biomechanical variables during running and cutting tasks. *Journal of Electromyography and Kinesiology*. 2016;30:137-142.

40. McFadden C, Daniels K, Strike S. The sensitivity of joint kinematics and kinetics to marker placement during a change of direction task. *J Biomech*. 2020;101.

41. Pohl MB, Lloyd C, Ferber R. Can the reliability of three-dimensional running kinematics be improved using functional joint methodology? *Gait Posture*. 2010;32(4):559-563.

42. Luciano F, Ruggiero L, Pavei G. Sample size estimation in locomotion kinematics and electromyography for statistical parametric mapping. *J Biomech*. 2021;122.

Chapter 4:

Effects of a Total Motion Release (TMR®) Intervention on Asymmetrical Movement Patterns

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Significance of the Chapter

The first two studies of this dissertation established that the single leg squat (SLS), forward step down (FSD), and lateral step down (LSD) each invoked different movement patterns. The SLS was shown to elicit patterns that would be best used when increased demand on the hip and pelvis in the sagittal plane is desired. Additionally, the SLS was shown to be sensitive for sagittal plane asymmetries at the hip and knee. For these reasons, the SLS was selected for further analyses using a rehabilitative protocol that has been proposed to correct movement disparities. Movement pattern asymmetries are commonly observed following injury and often occur alongside self-identified factors such as pain, tightness, limited range of motion, etc. However, little is known about the relationship between objective mechanical imbalances (e.g. kinematics, kinetics) and self-identified factors thought to limit function during the SLS. To begin assessing the importance of bilateral asymmetries, it is first necessary to understand the relationship between mechanical asymmetries, and perceived symptoms that are often related to injury. The next step would be to understand whether the resolution of these symptoms results in a reduction of the potentially asymmetrical movement. Thus, the relationship of self-perceived imbalances to mechanical imbalances, as well as the resolution of both perceived and mechanical imbalances would suggest that asymmetries are associated with factors of injury. Therefore, the final study of this dissertation will assess the effectiveness of rehabilitative protocol designed to correct movement imbalances related to pain, weakness, and instability during a SLS.

Key words: Movement asymmetries, Total Motion Release, Injury Prevention

Abstract

The potential for a unilateral training protocol to improve lower extremity movement symmetry would be of great benefit for rehabilitation protocols targeted at improving movement symmetry between legs. The Total Motion Release® (TMR®) protocol has been theorized to assess and improve movement asymmetries. Therefore, the purpose of this study was to examine whether self-identified imbalances with the TMR® scale coincided with kinematic and kinetic asymmetries during a SLS. The secondary purpose was to explore whether improving the self-scored imbalances resulted in decreased movement pattern asymmetries. Participant identified TMR® scores along with kinetic and kinematic lower extremity data were assessed bilaterally. The current study hypothesized that participants with self-identified imbalances greater than 10 on the TMR® scale would present with decreased range of motion (ROM), less squat depth, and reduced internal joint moments on the non-preferred side. A secondary hypothesis was that participants would reduce their scores on the non-preferred side after performing the unilateral training protocol. Lastly, it was hypothesized that after the training protocol, the deficits in ROM, squat depth, and joint moments would be increased, subsequently improving the symmetry between legs. Sagittal plane kinematic and kinetic waveforms for the SLS task were examined with Statistical Parametric Mapping (SPM) to evaluate bilateral mechanical differences. Main effects for bilateral asymmetries were found for knee flexion ($p < 0.01$, 7-45%), ankle dorsiflexion ($p < 0.01$, 11-36%), and knee flexion moments ($p < 0.01$, 7-50%). Participants were also found to have decreased TMR® scores on the non-preferred leg immediately following ($\Delta 15.0$, $p < 0.01$) and after the rest period ($\Delta 19.6$, $p < 0.01$). Main effects of treatment were found for knee flexion ($p < 0.01$, 48-67%), knee flexion moments ($p = 0.03$, 46-53%), and ankle dorsiflexion moments. In conclusion, bilateral asymmetries were identified at the group and single subject level using the TMR® scale. Additionally, the current study found reduced TMR® scores on the non-preferred leg following the unilateral training protocol, as well as increased internal knee flexion moments on the non-preferred leg after the intervention. However, overall squat depth did not increase on the non-preferred leg and bilateral asymmetries persisted after the intervention.

Introduction

Lower extremity movement symmetry is often established as a rehabilitation goal with patients who have had injuries that limit movement on one side of the body.[1] Injuries and their corresponding symptoms (e.g., pain, tightness, nervousness) have the potential to limit movement on that limb, which may result in a discrepancy between sides. For example, sprinters with prior hamstring injuries have been found to present with increased hip flexion as well as decreased knee flexion on the previously injured leg through the stance phase of sprinting,[2,3] while adults with anterior knee pain (AKP) have been found to have decreased hip flexion on the affected leg when performing a single leg squat (SLS).[4] Additionally, patients with femoral acetabular impingement syndrome (FAIS) have been found to have decreased hip and knee flexion, as well as overall squat depth on the affected leg during a SLS.[5] A commonality across these populations is that the injury is unilateral, which may provide practitioners with the opportunity to use the unaffected leg to achieve rehabilitation goals.

Total Motion Release® (TMR®) is a rehabilitation protocol theorized to reduce symptoms of dysfunction such as pain, tightness, and limited range of motion (ROM) by performing movements on the side contralateral to the symptomatic limb.[6–8] When using TMR®, a baseline series of six upper (arm raise, trunk twist, arm press) and lower extremity motions (SLS, straight leg raise, single leg sit to stand), are first performed and each motion is then rated on both sides using a scale from 0-100.[7,9] The higher the rating, the greater the patient’s symptoms, which may be related to subjective measures of stability, range of motion, pain, tightness, etc.[6] After an imbalance or imbalances are identified (i.e., a difference in scores between sides), the patient will self-treat by using the movement with the greatest imbalance and performing that motion on the side that scored lower (i.e., the preferred side).[7,10] Performing the exercises on the preferred side is thought to improve symptoms on the non-preferred side (i.e., the side that scored higher); thus, practitioners reduce the risk of exacerbating symptoms while potentially improving movement on the injured or affected side.

The TMR® protocol is theorized to work from a model of regional interdependence that infers a connectedness across body segments.[6] This theory is supported by studies that have found increased internal and external shoulder ROM by performing movements such as the trunk twist and arm raise;[9,10] while a TMR® protocol[8] using a trunk twist and straight leg raise was demonstrated to increase hip internal rotation. Although each of these studies observed regionally interdependent changes that resulted in greater ROM, no study has examined whether patient identified imbalances coincide with objective measures like kinematic and kinetic analyses. Additionally, evidence for whether performing one of the baseline motions (i.e., SLS) on the preferred side results in a reduction of the score on the non-preferred side is lacking.

Of the six primary TMR® movements, the SLS requires the most strength and coordination to perform. The SLS is also a commonly used task in rehabilitation due to its potential to identify unilateral deficits in movement,[11] as well as for its utility as a rehabilitative exercise for lower extremity injury.[12] The SLS movement mechanics (kinematics and kinetics) have also been correlated to higher velocity single leg movements such as jogging and jumping;[13,14] suggesting, joint mechanics during the SLS may transfer to movements that place greater forces on ligaments and soft tissue. Therefore, the purpose of this study was to evaluate whether perceived asymmetries identified by a TMR® scoring protocol related to mechanical asymmetries and whether improving perceived asymmetries influenced movement mechanics. The current study hypothesized that participants with self-identified imbalances greater than 10 on the TMR® scale would present with decreased range of motion (ROM) of the lower extremity joints resulting in a smaller squat depth and reduced internal joint flexion moments on the non-preferred side. A secondary hypothesis was that participants would reduce their scores (i.e., perceptions of dysfunction) on the non-preferred side after performing the unilateral training protocol, resulting in increased squat depth on the non-preferred leg, and improved mechanical symmetry.

Methods

Participants

Twenty-seven participants were recruited from a convenience sample for the current study. Of those 27 participants, 20 qualified for the study (10 female, 10 male; age = 24.1 ± 3.5 years; height = 173.8 ± 10.8 cm; mass = 72.0 ± 14.4 kg) with TMR® score imbalances ≥ 10 (non-preferred side scores = 50.2 ± 15.6, preferred side scores = 29.5 ± 17.2) during the

SLS. Participants with musculoskeletal pathologies (e.g., AKP, hamstring strains, hip impingement), or a prior history of orthopedic surgery, were eligible for inclusion in this study. Ineligibility was determined by having less than a 10-point discrepancy between legs during the SLS or if the participant was unable to perform the SLS within a self-determined range of pain tolerance on the non-preferred side. Participants with bilateral pain during the SLS were also considered ineligible to protect participants from exacerbating pain during the protocol. Participants who were using medications that could impair proprioceptive capabilities were also excluded. Prior to participation, all participants signed an informed consent form approved by the University of Idaho's internal review board.

Instrumentation

Three-dimensional marker trajectories were collected with an eight-camera motion capture system (200 Hz; VICON, Oxford Metric Ltd., Oxford, UK). Participants were equipped with 45 retro-reflective markers used to create a custom cluster-based model for the pelvis and lower extremities. The markers defined segments for the trunk and pelvis, as well as the thigh, shank, and foot bilaterally. A force-platform (1000 Hz; ORG-6, AMTI Inc., Watertown, MA, USA) temporally synchronized with the motion capture system was used to collect ground reaction forces (GRFs).

TMR® Pre-Post Procedures

Prior to the motion capture analysis, participants performed the SLS, and identified preferred and non-preferred sides using the TMR® protocol. The participants were first shown the TMR® rating scale which considered pain, tightness, range of motion (ROM), strength, tension, nervousness, quality, etc. Participants were asked to rate their SLS on the 0–100-point scale using the above criteria. The SLS began in a position with hip of the non-stance limb in a partially flexed position and the knee extended, with their hands on their waists. Hand position was to be maintained for the duration of the squat. Participants were then asked to squat down as far as they could without pausing at the bottom of the squat and without allowing the heel of their non-stance limb to touch the ground. This was performed a maximum of three times on each leg to identify their scores on each leg. The leg that scored higher was defined as the non-preferred leg and the leg that scored lower was defined as the preferred leg. A difference score was calculated between the two limbs by subtracting the lowest from the largest self-reported score. Participants who reported a bilateral difference score of 10 or greater were invited to continue through the remainder of the study (N=20). Participants with a reported difference of less than 10 were excluded from further study participation (N=7).

Following instrumentation, participants performed one SLS on each limb (starting with the non-preferred side) and rated each leg again on the 0-100 scale. This was performed to account for the potential of the attachments of the retro-reflective markers and clusters to affect the participants perception of the movement. This was the baseline score that was used for subsequent analyses. Participants then performed the SLS on each leg (starting with the non-preferred) to achieve eight ‘good’ trials to be used as their baseline data prior to the intervention. Due to the TMR® protocol using the preferred leg to perform the treatment, the non-preferred side was collected first to remove the potential of a treatment effect by continuing to perform repetitions of the SLS on the preferred leg. A trial was deemed as ‘not good’ and recollected if the participant performed the trial in a non-continuous manner (i.e., pausing at the bottom), or lost balance as determined by the stance foot moving out of its original position, or hands coming off their waist. The number of trials was based on prior statistical models that determined a minimum of seven trials was necessary to reach a statistical power of 0.8 for kinematic data during an SPM analysis.[15] Trials were performed at a participant selected rate to limit fatigue and squat velocity was not controlled for.

Following the collection of baseline data, participants performed the SLS TMR® intervention. This consisted of performing the SLS in sets of ten repetitions only on the preferred side. Participants were allowed to perform these squats at their own pace so long as they were able to complete them within 90 seconds. Symmetry of TMR® scores between the two legs was reassessed with one SLS on each leg (starting on the non-preferred side) after each set. Following the completion of the ten repetitions and reassessment of the TMR® scores, a rest period of 30 seconds was given between sets. If the self-reported score imbalances were resolved (i.e., the difference between sides was equal to zero) the intervention was completed, and participants moved on to perform the first post treatment assessment. The intervention was also stopped if the maximum number of four sets were performed without a symmetrical score being achieved. After the TMR® intervention, the participants again performed eight good trials on each leg, starting with eight on the non-preferred side. These SLSs were performed in the same manner as the baseline testing which allowed them to be performed at a self-selected rate. Following the first set of post-treatment SLSs, participants were asked to sit on a treatment table for 10-minutes in an attempt to wash-out the immediate treatment effect. After 10-minutes had elapsed, participants reassessed their score by performing one SLS on each leg. Then, eight more single leg squats were collected bilaterally, starting on the non-preferred side, following the same instructions as the baseline and first post-treatment protocol.

Data Analysis

Angular kinematics and kinetics were computed using a Cardan (X-Y-Z) rotation sequence with Visual 3D software (v6, C-Motion Inc., Germantown, MD, USA). Marker trajectories were filtered using a low-pass, fourth-order Butterworth filter at 6 Hz.[16,17] Ground reaction force data were filtered using a low-pass, fourth order Butterworth filter with a cutoff frequency of 10 Hz.[16] Kinematic marker positions and ground reaction force data were used to calculate internal joint moments from an inverse dynamics model within the Visual 3D software. Moments were normalized to body mass and calculated so that internal flexion moments for the hip, knee, and ankle were represented by positive values.

Statistical parametric mapping (SPM) analyses were used to assess joint angles and moments. The kinematic and kinetic time-series were interpolated to 101 data points (100% of cycle) using a custom MATLAB script (MathWorks, Natick, MA, USA). During the first second of each task, participants were asked to hold their position to achieve 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 waveform during the quiet stance period.[18] The end of the task was defined as the point when hip flexion angle returned to that starting value. Center of mass (COM) vertical displacement was used to determine squat depth.[19] This was calculated by normalizing each participants data to the highest vertical point of their COM within a given trial and resulted in a net vertical displacement in cm.

Statistical Analysis

A 2x3 repeated measures ANOVA was used to assess differences of TMR® scores between the preferred and non-preferred legs at Baseline, post-treatment (Post1), and 10-minutes post-treatment (Post2) in R (The R Foundation for Statistical Computing Platform, 2021). The significance level for statistical analyses of TMR® scores was set a priori to $\alpha \leq 0.05$. Significant main effects were followed up with post hoc t-tests and Bonferroni alpha corrections. Interactions were followed up with separate one-way ANOVAs for time on each leg and followed up with t-tests and Bonferroni corrections when the ANOVA indicated a difference. Additionally, the effect of leg at each time point was assessed with follow up paired t-tests and alpha corrections. Effect sizes were calculated for TMR® scores using partial eta squared values that were interpreted as small (η_p^2 = 0.01), medium (η_p^2 = 0.06), and large (η_p^2= 0.14), and Cohen's *d* values were calculated for pairwise comparisons and interpreted as small (*d* = 0.2), medium (*d* = 0.5), and large (*d* = 0.8).[20]

Separate 2x3 repeated measures ANOVAs were also used to compare kinetic and kinematic waveforms for the preferred and non-preferred limbs at each of the three time points using an open-source software package spm1D 0.4.[21] Significant results from the repeated measures ANOVAs were followed up with post hoc t-tests as well as SS analyses. The significance level for all SPM tests was set a priori to $\alpha \leq 0.05$. For the SPM analyses, an alpha correction was not deemed appropriate because the procedure requires independence across the tests which is not the case with time-series data.[22] Additionally, SPM analyses have been shown to reduce type I error associated with kinematic data.[22,23] For group data, the participant's mean values of the eight trials, for both the preferred and non-preferred legs, were calculated for each task and used for analysis. For the single subject (SS) analyses, the eight trials were compared between the two legs for each task. When the participant's statistical difference between legs crossed the critical threshold, the timing of this cross from 0-100% of the movement was recorded. If a cumulative 10% or more of the task reached statistical difference, the participant was classified as containing an asymmetry and reported as a percentage of the population. As some participants were found to have significant differences only during the first or last five percent of the trial, and these findings may lack clinical implications, the cutoff percentage of 10% was used to limit inflation for number of participants with significant differences between legs. Descriptive statistics of peak values and the maximum differences between waveforms at the group level were also recorded (Table 1).

Results

TMR® scores

An interaction of leg and time ($p < 0.01$, $\eta_p^2 = 0.05$) was found for TMR® scores. The one-way ANOVA for the preferred leg found no effect of time on score ($p = 0.91$, $\eta_p^2 = 0.00$). A significant effect of time was found for the non-preferred leg ($p < 0.01$, $\eta_p^2 = 0.19$). *Post hoc t-tests* indicated a significant difference between Baseline and Post1 (Δ15.0, p < 0.01, d = 0.85) and from Baseline to Post2 (Δ19.4, $p < 0.01$, d = 1.17); however, there was no effect of time between Post1 and Post2 (Δ4.4, $p = 0.06$, d = 0.23). There was an effect of leg at Baseline (Δ20.7, $p < 0.01$, d = 1.25), Post1 (Δ5.9, $p = 0.04$, d = 0.31), but not at Post2 (Δ3.4, $p = 0.26$, d = 0.20). Immediately following the intervention 55% of participants achieved an equal (symmetrical) score between legs.

Kinematics

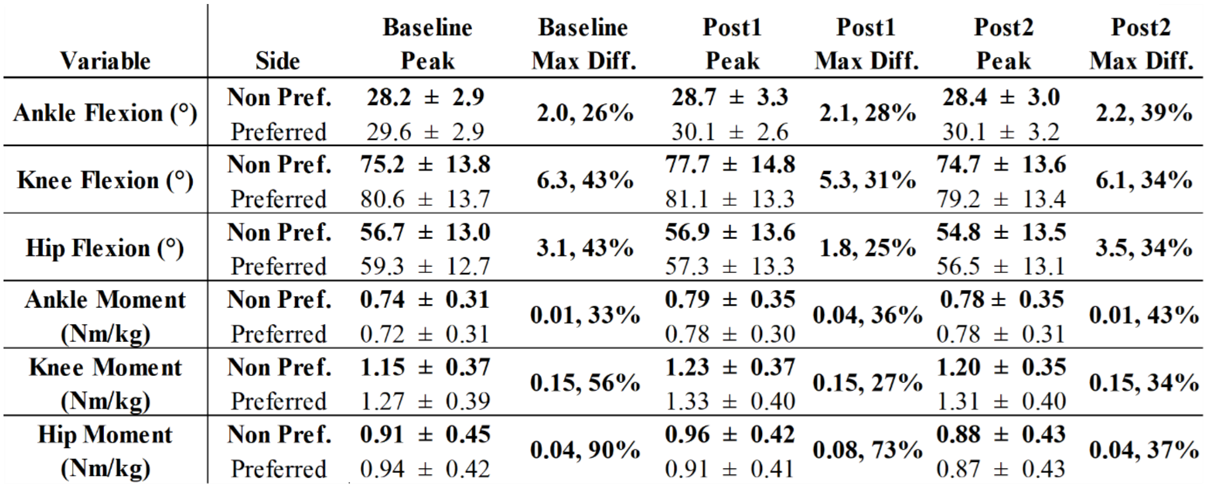
A main effect of time was found for COM displacement ($p < 0.01$, timing = 53-66%) and the *post hoc t-tests* indicated a significant difference between Post1 and Post2 on the non-preferred leg ($p < 0.01$) from 27-65% of the movement and with 55% of participants demonstrating a significant difference. For hip flexion, there was a main effect of time ($p = 0.02$, timing = 3-23%, $p < 0.01$, timing = 55-83%) with the *post hoc* tests indicating significant differences on the non-preferred leg between Baseline and Post1 ($p = 0.04$, timing = 8-15%, SS = 30%), Baseline and Post2 ($p < 0.01$, timing = 7-23%, SS = 60%), and from Post1 to Post2 ($p < 0.01$, timing = 32-66%, SS = 30%). The effect of time for hip flexion on the preferred leg was significant between Baseline and Post1 ($p = 0.03$, timing = 7-17%, SS = 50%), and from Baseline to Post2 ($p = 0.03$, timing = 62-70%, SS = 65%). Knee flexion was found to have a significant main effect of time ($p < 0.01$, timing = 48-67%) and leg ($p < 0.01$, timing = 7-45%). Post hoc tests of time for knee flexion indicated a significant difference from Post1 to Post2 ($p < 0.01$, timing = 48-63%, SS = 30%) on the non-preferred side. The effect of leg was found to be statistically significant at Baseline ($p < 0.01$, timing = 4-43%, SS = 60%), Post1 ($p < 0.01$, timing = 62-70%, SS = 65%), and Post2 ($p < 0.01$, timing = 12-34%, SS = 70%). Ankle dorsiflexion was found to have a main effect of leg ($p < 0.01$, 11-

36%) with post hoc tests indicating significant differences at Baseline ($p < 0.01$, timing = 5-27%, SS = 50%), Post1 ($p = 0.04$, timing = 18-21%, SS = 55%), and at Post2 ($p < 0.01$, timing = 18-40%, SS = 60%). Descriptive statistics for discrete values from kinematic waveforms are provided in Table 1.

Joint Moments

No main effects were observed for internal hip flexion moments. Knee flexion moments demonstrated a significant effect of time ($p = 0.03$, timing = 46-53%) and leg ($p < 0.01$, timing = 7-50%). Post hoc tests indicated that there was a significant difference between Baseline and Post1 ($p < 0.01$, timing = 45-59%, SS = 45%) for the non-preferred leg. Significant differences were observed between legs at Baseline ($p < 0.01$, timing = 8-27%, SS = 50%), Post1 ($p < 0.01$, timing = 12-34%; $p < 0.01$, timing = 90-97%, SS = 60%), and Post2 ($p < 0.01$, timing = 12-39%, SS = 20%). Ankle flexion moments were found to have a significant effect of time ($p = 0.02$, timing = 41-55%; $p = 0.03$, 74-100%). The non-preferred side had significant findings from the post hoc tests for Baseline-Post1 ($p = 0.02$, timing = 85-99%, SS = 15%), Baseline-Post2 ($p = 0.04$, timing = 89-92%, SS = 30%), and on the preferred side from Baseline to Post1 ($p = 0.02$, timing = 44-51%; $p = 0.03$, 93-97%, SS = 15%). Descriptive statistics for discrete values from kinetic waveforms are provided in Table 1.

Table 4. 1 Descriptive data for peak joint angles and moments at baseline, post treatment (Post1) and 10-minutes post treatment (Post2). Max difference indicates the maximum difference between waveforms and the percentage of the cycle where that occurred.



Variable	Side	Baseline Peak	Baseline Max Diff.	Post1 Peak	Post1 Max Diff.	Post2 Peak	Post2 Max Diff.
Ankle Flexion (°)	**Non Pref.**	**28.2 ± 2.9**	**2.0, 26%**	**28.7 ± 3.3**	**2.1, 28%**	**28.4 ± 3.0**	**2.2, 39%**
	Preferred	29.6 ± 2.9		30.1 ± 2.6		30.1 ± 3.2	
Knee Flexion (°)	**Non Pref.**	**75.2 ± 13.8**	**6.3, 43%**	**77.7 ± 14.8**	**5.3, 31%**	**74.7 ± 13.6**	**6.1, 34%**
	Preferred	80.6 ± 13.7		81.1 ± 13.3		79.2 ± 13.4	
Hip Flexion (°)	**Non Pref.**	**56.7 ± 13.0**	**3.1, 43%**	**56.9 ± 13.6**	**1.8, 25%**	**54.8 ± 13.5**	**3.5, 34%**
	Preferred	59.3 ± 12.7		57.3 ± 13.3		56.5 ± 13.1	
Ankle Moment (Nm/kg)	**Non Pref.**	**0.74 ± 0.31**	**0.01, 33%**	**0.79 ± 0.35**	**0.04, 36%**	**0.78 ± 0.35**	**0.01, 43%**
	Preferred	0.72 ± 0.31		0.78 ± 0.30		0.78 ± 0.31	
Knee Moment (Nm/kg)	**Non Pref.**	**1.15 ± 0.37**	**0.15, 56%**	**1.23 ± 0.37**	**0.15, 27%**	**1.20 ± 0.35**	**0.15, 34%**
	Preferred	1.27 ± 0.39		1.33 ± 0.40		1.31 ± 0.40	
Hip Moment (Nm/kg)	**Non Pref.**	**0.91 ± 0.45**	**0.04, 90%**	**0.96 ± 0.42**	**0.08, 73%**	**0.88 ± 0.43**	**0.04, 37%**
	Preferred	0.94 ± 0.42		0.91 ± 0.41		0.87 ± 0.43	

Discussion

This study included participants with bilateral TMR® score differences between preferred and non-preferred legs (Δ 20.7). Increased values were observed on the preferred leg for knee flexion, ankle flexion, and knee flexion moments (Figure 4.1). Overall, 75% of the current study's sample had an asymmetry for at least one of the aforementioned variables. On the preferred leg, 83% percent of participants with a bilateral difference had increased knee flexion and 90% had increased ankle flexion and knee flexion moments on that leg.

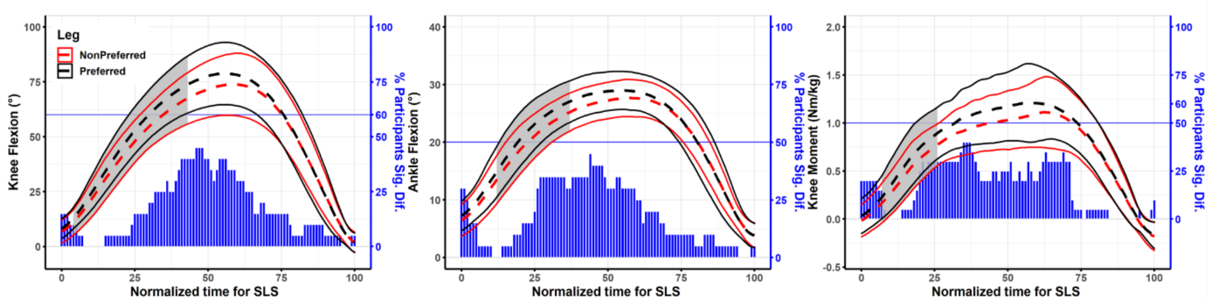


Figure 4.1 Time series analyses comparing preferred and non-preferred legs at Baseline. Shaded areas represent the time when statistical differences were found (p<0.05). Vertical blue bars indicate the percentage of participants with a significant difference at each percentage of the task. Horizontal blue line indicates the total percentage of participants with a significant difference.

Thus, the SS analyses support the findings at the group level. The current findings provide initial evidence that self-identified asymmetries with the TMR® scale for a SLS are related to deficits in knee flexion, ankle flexion, and knee flexion moments during a SLS. This is an important finding as bilateral differences can often be masked at the group level due to intraparticipant variability or defining limb dominance based on the leg used to kick a ball.[24,25] Thus, the TMR® scale could be used as an effective instrument for identifying preferred and non-preferred legs during movement screen scenarios, or when assessing single leg weightbearing movement prior to developing rehabilitative protocols.

Following the intervention, the average participant was able to perform the SLS with greater internal knee flexion moments on the non-preferred leg, with 40% of participants demonstrating increased knee flexion moments between Baseline and Post1 (Figure 4.2). Of those eight participants, seven also had reduced perceptions of dysfunction (average Δ Baseline-Post1 = 16.5), suggesting that improved TMR® scores are sensitive to changes in loading the knee during the SLS. Participants maintained this gain after the 10-minute cool-down period as there was no effect of time between Post1 and Post2 for internal knee flexion moments. However, clinicians should be cognizant of the potential for patients to not respond in this manner as less than half of our sample increased loads at the knee. As this protocol requires limited contribution from the non-preferred leg, mitigating the risk of exacerbating symptoms, TMR® should still be considered during rehabilitation protocols where patients are reluctant to perform SLSs on one side due to factors such as pain, tightness, limited ROM, etc.

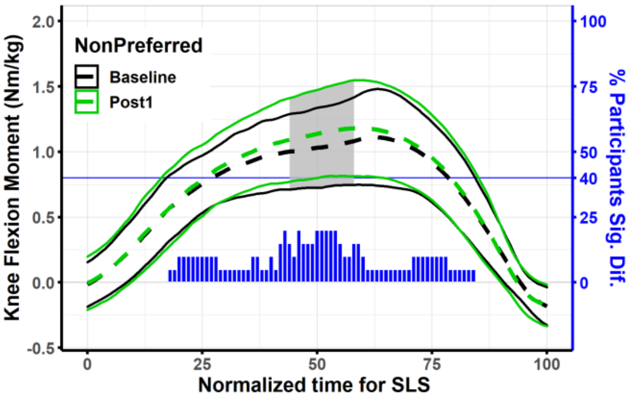


Figure 4.2 Time series analyses comparing the non-preferred leg at Baseline and Post1. Shaded areas represent the time when statistical differences were found (p<0.05). Vertical blue bars indicate the percentage of participants with a significant difference at each percentage of the task. Horizontal blue line indicates the total percentage of participants with a significant difference.

The current findings are the first to indicate that performing one of the primary TMR® motions on the preferred leg can improve TMR® scores on the non-preferred leg (Figure 4.3). Prior studies7–10 have not reported these measures but have demonstrated the potential effectiveness of a TMR® intervention to increase ROM. However, the current study only found a slight change in hip flexion following the SLS intervention (p = 0.03, 7-17% of SLS). This finding may not be clinically significant as there was only a 0.2° average increase in hip flexion. Additionally, of the six participants who had a bilateral difference (30% of the population), three increased hip flexion, and three had decreased hip flexion on the non-preferred leg immediately after the intervention. Although, increased knee moments were observed and 55% of the participants had resolved TMR® scores following the intervention, squat depth did not increase, and bilateral differences were still present (Figure 4.4). Thus, improvements in TMR® scores may coincide with mechanical

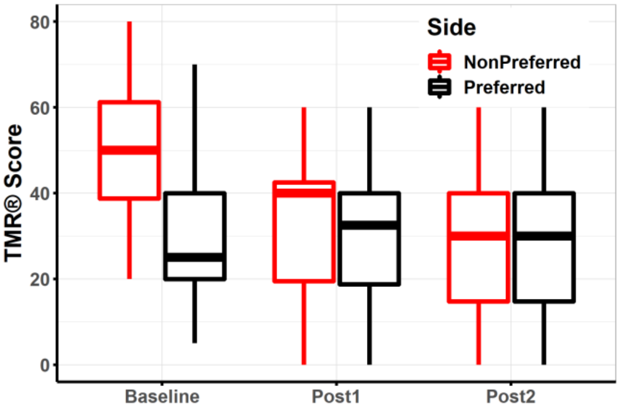


Figure 4. 3 Box plots comparing TMR® scores between legs at Baseline, immediately following the intervention (Post1), and 10-minutes after the intervention (Post2).

changes at the knee but do not necessarily result in visually observable changes for clinical measures of movement.

The current findings are partially corroborated by a case-series[26] that found a TMR® intervention resulted in clinically important differences in pain scores for patients experiencing AKP. The case-series[26] also found that the functional measures of single leg weightbearing were unchanged after a TMR® intervention. A reduction in self-identified factors of dysfunction with no visually observable changes for SLS mechanics has not been limited to the TMR® paradigm. For example, investigations into different taping techniques[27,28] intended to improve AKP have found that symptoms were reduced following the tape application but did not impact SLS kinematics. A reduction of pain during the SLS has been attributed to changes in quadriceps muscle activation;[27] however, pain effects beyond biomechanical explanations (i.e., placebos) should also be considered as an explanation. The potential of interventions such as TMR® or taping to acutely improve symptoms during a SLS could be useful during rehabilitation but clinicians may want to supplement these interventions with longer-term training protocols that have been found to improve kinematic variables.[29]

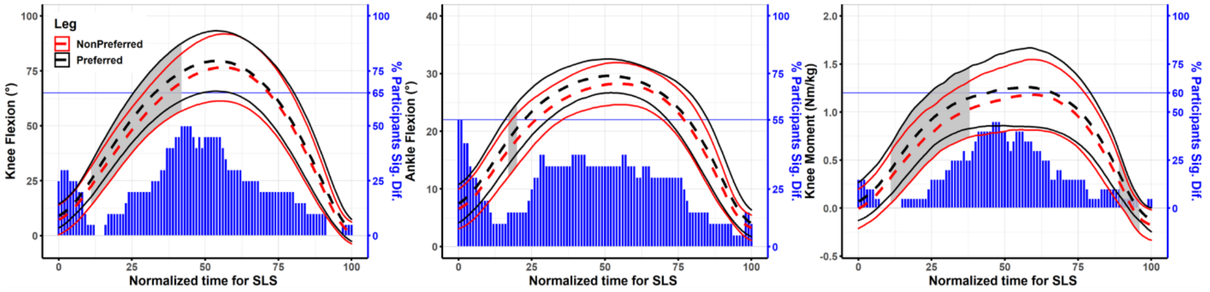


Figure 4.4 Time series analyses comparing preferred and non-preferred legs at Post1. Shaded areas represent the time when statistical differences were found ($p<0.05$). Vertical blue bars indicate the percentage of participants with a significant difference at each percentage of the task. Horizontal blue line indicates the total percentage of participants with a significant difference.

Although bilateral differences were identified by using the TMR® scale, the importance of the mechanical bilateral differences during a SLS is disputed.[25] A longitudinal study found that practitioner rated bilateral differences in the frontal plane at 90° of knee flexion were not indicative of non-contact anterior cruciate ligament injury.[30] However, by not including potential differences for sagittal plane asymmetries of the lower extremity, longitudinal studies may limit potential findings as it relates to injury risk. Longitudinal studies for bilateral differences have also neglected to include a SS approach for the identification of asymmetries[25] or focused on the leg used to kick a ball.[26] As leg dominance has been found to be task specific,[26,27] and bilateral kinematic differences can be masked at the group level,[27] the inclusion of a SS approach is necessary to fully understand the importance of injury risk as it relates to movement symmetry. Additionally, investigators should consider the potential of the bilateral movement imbalances found in the current study to coincide with more functional movements such as walking and running, subsequently identifying whether these potential imbalances elicit chronic lower extremity injuries through increased repetitive loads at the knee and ankle on the non-preferred leg. As the TMR® screen for the SLS can be performed in a few minutes, its use as an instrument to track injury risk from bilateral asymmetries may be warranted.

The current study has its limitations. First, only one movement from the six primary TMR® motions for movement assessment was included. As TMR® is often thought to identify regionally imbalances throughout the body that may be connected,[6] only assessing one of these movements may have missed the root cause of the dysfunction and limited the effectiveness of the treatment. However, as the core foundation of the treatment is to use movement on one side of the body to improve movement on the other, it is essential to establish the efficacy of this fundamental concept for the paradigm. The current study's protocol also differed from the TMR® protocol in the number of sets and repetitions (2x15-20) that are typically performed prior to reassessing the TMR® score.[6,7] Per the TMR® protocol, if an observed improvement (score decreased by ≥ 10) is not found after the first reassessment, a change is made to the treatment that could increase the intensity (e.g., performing the repetitions faster).[6] Thus, a lack of treatment dosage and omitting changes to the treatment protocol may have influenced the outcomes of this study, and is a factor that could be considered by future studies examining TMR®. Lastly, the observed decrease in TMR® scores is less than what has been reported as a minimal detectable change (26.1) using the TMR® scale for the SLS.[6] This may not directly translate to the current results though, as the reliability study did not assess scores before and after a TMR® treatment.

Conclusion

The results of the current study indicate that a TMR® assessment for the SLS can identify bilateral mechanical differences between legs at the group and SS level. Performing sets of the SLS on the preferred leg can reduce symptoms related to pain, tightness, and stability on the contralateral leg and enable increased loading of the non-preferred knee. However, equalizing TMR® scores after the intervention did not affect bilateral asymmetries or increase squat depth on the non-preferred leg. Future longitudinal investigations are necessary to ascertain the importance of SLS movement symmetry as it relates to developing self-identified factors of dysfunction and potential injury risk.

References

1. Benjaminse A, Holden S, Myer GD. ACL rupture is a single leg injury but a double leg problem: Too much focus on "symmetry" alone and that's not enough! *Br J Sports Med*. 2018;52(16):1029-1030.

2. Ciacci S, Di Michele R, Fantozzi S, Merni F. Assessment of Kinematic Asymmetry for Reduction of Hamstring Injury Risk Injury Prevention. *IJATT*. 2013;18(6):18-23.

3. Daly C, Mccarthy Persson U, Twycross-Lewis R, Woledge RC, Morrissey D. The biomechanics of running in athletes with previous hamstring injury: A case-control study. *Scand J Med Sci Sports*. 2016;26(4):413-420.

4. Severin AC, Burkett BJ, McKean MR, Wiegand AN, Sayers MGL. Limb symmetry during double-leg squats and single-leg squats on land and in water in adults with long-standing unilateral anterior knee pain; a cross sectional study. *BMC Sports Sci Med Rehabil*. 2017;9(1).

5. Malloy P, Wichman DM, Garcia F, Espinoza-Orías A, Chahla J, Nho SJ. Impaired Lower Extremity Biomechanics, Hip External Rotation Muscle Weakness, and Proximal Femoral Morphology Predict Impaired Single-Leg Squat Performance in People With FAI Syndrome. *American Journal of Sports Medicine*. Published online 2021.

6. Miley EN, Reeves AJ, Casanova MP, Martonick NJP, Baker J, Baker RT. Test–retest reliability of the Total Motion Release® scale. *J Sport Rehabil*. 2021;30(6):961-964.

7. Strauss AT, Parr AJ, Desmond DJ, Vargas AT, Baker RT. The effect of total motion release on functional movement screen composite scores: A randomized controlled trial. *J Sport Rehabil*. 2020;29(8):1106-1114.

8. Dexter RRoss, Loftis TK, Pettaway AN, Baker RT, May J. The Immediate Effects of a Total Motion Release® Warm-Up on Active Rotational Hip Range of Motion in Overhead Athletes. *Int J Sports Phys Ther*. 2019;14(6):898-910.

9. Gamma SC, Baker R, May J, Seegmiller JG, Nasypany A, Iorio SM. Comparing the Immediate Effects of a Total Motion Release Warm-Up and a Dynamic Warm-Up

Protocol on the Dominant Shoulder in Baseball Athletes. *J Strength Cond Res*. 2018;34(5):1362-1368.

10. Gamma SC, Baker RT, Iorio S, Nasypany A, Seegmiller JG. A Total Motion Release Warm-Up Improves Dominant Arm Shoulder Internal and External Rotation in Baseball Players. *Int J Sport Phys Ther.* 2014;9(4):509-517.
11. Nakagawa TH, Moriya ET, Maciel CD SFV. Trunk, Pelvis, Hip, and Knee Kinematics, Hip Strength, and Gluteal Muscle Activation During a Single-Leg Squat in Males and Females With and Without Patellofemoral Pain Syndrome. *J Ortho Sports Phys Ther*. 2012;42(6):491-501.
12. Graci V, Salsich GB. Trunk and lower extremity segment kinematics and their relationship to pain following movement instruction during a single-leg squat in females with dynamic knee valgus and patellofemoral pain. *J Sci Med Sport*. 2015;18(3):343-347.
13. Munro A, Herrington L, Comfort P. The relationship between 2-dimensional knee-valgus angles during single-leg squat, single-leg-land, and drop-jump screening tests. *J Sport Rehabil*. 2017;26(1):72-77.
14. Whatman C, Hing W, Hume P. Kinematics during lower extremity functional screening tests-Are they reliable and related to jogging? *Physical Therapy in Sport*. 2011;12(1):22-29.
15. Luciano F, Ruggiero L, Pavei G. Sample size estimation in locomotion kinematics and electromyography for statistical parametric mapping. *J Biomech*. 2021;122.
16. Khuu A, Foch E, Lewis CL. Not All Single Leg Squats Are Equal: a Biomechanical Comparison of Three Variations. *Int J Sports Phys Ther*. 2016;11(2):201-211.
17. Lewis CL, Foch E, Luko MM, Loverro KL, Khuu A. Differences in lower extremity and trunk kinematics between single leg squat and step down tasks. *PLoS One*. 2015;10(5).
18. McMahon JJ, Suchomel TJ, Lake JP, Comfort P. Understanding the key phases of the countermovement jump force-time curve. *Strength Cond J*. 2018;40(4):96-106.

19. Martonick NJP, McGowan CP, Baker RT, Larkins LW, Seegmiller JG, Bailey JP. Comparison of Three Single Leg Weightbearing Tasks with Statistical Parametric Mapping. *Biomechanics*. 2022;2(4):591-600.

20. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. L. Erlbaum Associates; 1988.

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

22. Houston A, Fong DTP, Bennett AN, Walters V, Barker-Davies RM. Biomechanical differences between military patients with patellar tendinopathy and asymptomatic controls during single-leg squatting and gait – A statistical parametric mapping study. *Clinical Biomechanics*. 2021;90:105514.

23. Pataky TC. rft1d: Smooth one-dimensional random field upcrossing probabilities in Python. *J Stat Softw*. 2016;71.

24. Martonick NJP, Chun Y, Krumpl L, Bailey JP. Lower Extremity Kinematic Waveform Analysis During a Single Leg Drop Task – Including a Single Subject Design. *Int J Sports Phys Ther*. 2022;17(7):1271-1281.

25. Nordin AD, Dufek JS, James CR, Bates BT. Classifying performer strategies in drop landing activities. *J Sports Sci*. 2017;35(18):1858-1863.

26. Marcie Fyock, Nasypany AM, May J, Ambegaonkar J, Larkins L. *An Analysis of Patient Outcomes When Applying the Total Motion Release ® Technique to Treat Patients with Patellofemoral Pain Syndrome: A Dissertation of Clinical Practice Improvement*.; 2016.

27. Song CY, Huang HY, Chen SC, Lin JJ, Chang AH. Effects of femoral rotational taping on pain, lower extremity kinematics, and muscle activation in female patients with patellofemoral pain. *J Sci Med Sport*. 2015;18(4):388-393.

28. Clifford AM, Dillon S, Hartigan K, O’Leary H, Constantinou M. The effects of McConnell patellofemoral joint and tibial internal rotation limitation taping techniques in people with Patellofemoral pain syndrome. *Gait Posture*. 2020;82:266-272.

29. Dawson SJ, Herrington L. Improving single-legged-squat performance: Comparing 2 training methods with potential implications for injury prevention. *J Athl Train*. 2015;50(9):921-929.

30. Petu E, Nilstad A, Bahr R, Krosshaug T. Drop jump? single-leg squat? not if you aim to predict anterior cruciate ligament injury from real-time clinical assessment: A prospective cohort study involving 880 elite female athletes. *J Orthop Sports Phys Ther*. 2021;51(7):372-378.

Chapter 5: Overall Dissertation Conclusion

By

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Conclusion

The purpose of this dissertation was to examine the differences in movement patterns between three single leg weightbearing tasks (e.g., SLS, FSD, LSD) and whether performing these tasks resulted in asymmetrical movement patterns. To address this purpose, two separate data collections were performed. Data from the former data collection were analyzed with the aim to: 1) examine the differences in movement patterns between tasks, and (2) evaluate whether one of these tasks was better suited to identify asymmetrical movement patterns. The final study explored the potential of a subjective self-scored rating scale to identify bilateral differences at the group level, and whether improving scores on the rating scale coincided with a reduction in bilateral differences.

Clear differences were found between tasks that may guide their use in clinical practice. Differences in movement patterns on the weightbearing leg occurred due to the subtle changes between the non-weightbearing leg position and task demands during the SLS, FSD, and LSD. The FSD task may be best applied to movement screens that want to target excessive frontal plane knee motion. Whereas the SLS would be most useful for exercises that want to place demands on the muscles of the hip in the sagittal plane. The LSD task reduced frontal plane trunk motion relative to the other two tasks and may be best used to limit frontal plane knee torque during rehabilitation.

The secondary analysis from the first data collection found that each of these tasks elicited different bilateral differences among individuals; however, there were minimal differences at the group level when comparing preferred and non-preferred legs during the FSD, LSD, and SLS. Interestingly, individual analyses were necessary to elucidate when and whether bilateral differences occurred. Results from individual analyses indicated that bilateral symmetry through the complete FSD, LSD, and SLS movements is uncommon in healthy individuals. Clinicians can use the FSD and SLS when identifying sagittal plane imbalances, while the LSD invokes more asymmetrical movement patterns at the pelvis and trunk in the frontal plane. Although the relationship of movement asymmetries to injury risk remains disputed, the current evidence has focused on frontal plane motion, and group data that uses the leg for kicking to define dominance. For future studies to accurately assess the impact of movement symmetry, sagittal plane imbalances and individual analyses are necessary.

The selection of the SLS was made for further evaluation in the final study because the findings from the first study demonstrated that the SLS increased muscular demand on the hip relative to the other two tasks. Additionally, the results of the second study highlighted the SLS as a task for eliciting movement pattern imbalances in the sagittal plane. For the final study, the SLS was assessed before and after a Total Motion Release (TMR®) rehabilitative intervention theorized to improve bilateral asymmetries. The intervention used a self-identified score for factors such as pain, tightness, stability, and limited range of motion to assess each leg. These factors were hypothesized to limit squat depth on the leg that scored higher due to feelings of dysfunction during the SLS.

Similar to the second study, results of individual analyses in the final study also revealed sagittal plane kinetic and kinematic imbalances throughout the movement for the SLS. However, the final study also found bilateral differences at the group level for knee position and joint moments. It is likely that the findings at the group level in the final study were due to the added inclusion of the rating scale and threshold for inclusion which yielded perceived differences between legs for the abovementioned factors at baseline testing. Thus, researchers investigating bilateral differences at the group level should consider the methods of the final study when dichotomizing legs during the SLS. Additionally, clinicians should be aware that the non-preferred leg (i.e., the leg that had a higher TMR® score) is likely to present as decreased knee flexion, ankle flexion, and internal knee flexion moments. Following the intervention, the self-identified scores equalized between legs. This result coincided with the average participant increasing the amount of internal knee flexion torque that they could apply to their knee during the SLS following the intervention. However, the bilateral mechanical imbalances that were present at baseline persisted after the intervention. Therefore, clinicians should consider the potential for a TMR® intervention to improve factors such as pain, tightness, stability, and limited range of motion during the SLS; however, objective measures of movement should be tracked alongside TMR® scores when assessing the progress of rehabilitation.

The overall results of this dissertation indicate: 1) single leg movement tasks should not be used interchangeably, and the mechanical demands of each task may best suit specific screening or rehabilitative protocols, 2) incongruities between group and individual analyses indicated that it is necessary to include individual analyses when assessing movement pattern asymmetries, and 3) including objective measures of patient perceptions is required to dichotomize legs for group analyses. Future studies should begin to examine the importance of the observed movement asymmetries by considering individual analyses in conjunction with patient reported scales while performing longitudinal injury tracking.

Appendex 1: Chapter 1 Article Copyright

The article comprising Chapter 2 titled “Comparison of Three Single Leg Weight Bearing Tasks with Statistical Parametric Mapping” has been published in *Biomechanics.* The publisher for *Biomechanics*, MDPI, allows the authors to retain copyright (https://www.mdpi.com/authors/rights). Therefore, no copyright approval was required for this manuscript.

The article comprising Chapter 3 titled “Influence of Lateral Preference and Single Subject Analyses on Three Single Leg Movement Screens” has been submitted to *Physical Therapy in Sport* under the publisher *Elsevier* and has not yet been accepted or rejected for peer review.

The article comprising Chapter 4 titled “Effects of a Total Motion Release (TMR®) Intervention on Asymmetrical Movement Patterns” has been submitted to the *International Journal of Sport Physical Therapy* of the *North American Sports Medicine Institute (NASMI)*