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Position of the non-stance leg during the single leg squat affects females and males differently

Anne Khuu*, Cara L. Lewis

Boston University, Department of Physical Therapy & Athletic Training, PhD Program in Rehabilitation Sciences, College of Health & Rehabilitation Sciences: Sargent College, 635 Commonwealth Ave, Boston, MA 02215, USA

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ABSTRACT

Background: Kinematic differences between females and males for the single leg squat (SLS) have been identified. However, kinetic differences between sexes and how variations of the non-stance leg position during the SLS may affect kinematics and kinetics differently in females and males have not been examined.
Objectives: Examine sex-specific kinematic and kinetic differences during the SLS task with 3 different non-stance leg positions.
Design: Controlled laboratory study, cross-sectional design.
Methods: Thirty-two healthy adults (16 females, 16 males) performed the 3 SLS tasks while data were collected using a motion capture system and force plates. At 60 degrees of knee flexion (60KF) and peak knee flexion (PKF), kinematics and joint moments were compared between sexes and SLS tasks using a linear regression analysis.
Results: Females exhibited less ipsilateral trunk flexion ($P < 0.001$) and greater anterior pelvic tilt ($P \le 0.021$) and hip adduction ($P < 0.001$) than males across tasks at 60KF and PKF. Across tasks, females had a smaller knee flexion moment than males at PKF ($P = 0.001$). Females had a greater hip abduction moment during SLS-Front than SLS-Middle ($P = 0.044$) and SLS-Back ($P = 0.003$) at PKF, but males had similar hip abduction moments across tasks ($P \ge 0.299$). At 60KF, males had a greater knee adduction moment during SLS-Front compared to the other tasks ($P \le 0.019$) while females had similar hip abduction moments across tasks ($P \ge 0.459$).
Conclusion: Altering the non-stance leg position during the SLS affects the kinematics and kinetics of both females and males. The position of the non-stance leg can be modified for assessment and treatment purposes and should be reported in research.

1. Introduction

Clinicians often use single leg functional movement tasks, such as the single leg squat (SLS), to assess for impaired movement patterns in the trunk and lower extremity. The position of the non-stance leg during the SLS is not commonly standardized in clinical practice nor reported in research (Warner et al., 2019). The position of the non-stance leg, however, affects the kinematics of the trunk, pelvis, and lower extremity as well as the kinetics of the lower extremity in healthy females (Khuu, Foch, & Lewis, 2016). It is unclear if males are affected in the same way as females when the position of the non-stance leg during the SLS is varied.

Healthy females and males perform several single leg tasks differently including single leg landing (Jacobs, Uhl, Mattacola,

* Corresponding author.
E-mail addresses: akhuu@bu.edu (A. Khuu), lewisc@bu.edu (C.L. Lewis).

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Shapiro, & Rayens, 2007; Schmitz, Kulas, Perrin, Riemann, & Shultz, 2007), single leg stepdown (Earl, Monteiro, & Snyder, 2007), and SLS (Graci, Van Dillen, & Salsich, 2012; Weeks, Carty, & Horan, 2015; Zeller, McCrory, Kibler, & Uhl, 2003). Specifically, for the SLS, healthy females display less trunk flexion (Graci et al., 2012; Zeller et al., 2003), and more transverse plane pelvic rotation toward the non-stance leg (Graci et al., 2012; Weeks et al., 2015), hip adduction (Graci et al., 2012; Weeks et al., 2015; Zeller et al., 2003), and knee abduction (Graci et al., 2012) than healthy males. Zeller et al. (2003) also reported that females performed the SLS with less ipsilateral trunk flexion than males, although Graci et al. (2012) and Weeks et al. (2015) did not find any differences at the trunk. Despite some inconsistencies among these studies, they suggest that healthy females and males may display different movement patterns when performing the SLS. While these studies examined the SLS in females and males, they did not evaluate differences in non-stance leg position and did not address kinetic differences between sexes.

The purpose of this study was to examine sex-specific kinematic and kinetic differences during the SLS between 3 different non-stance leg positions in healthy females and males. We hypothesized that there would be both kinematic and kinetic differences between females and males for the 3 SLS tasks, and that these differences would be affected by the position of the non-stance leg.

2. Methods

2.1. Study design

A repeated measures design was used for this controlled laboratory study to compare trunk, pelvic, and lower extremity kinematics and lower extremity kinetics between females and males for the 3 SLS tasks. An *a priori* power analysis was conducted to determine the minimum sample size. Based on the hip adduction angles at peak knee flexion (a primary variable of interest) from Graci et al. (2012), an alpha of 0.05, and a beta of 0.20, a minimum of 10 participants per group was needed to adequately power this study.

2.2. Participants

A convenience sample of healthy adults was recruited. Sixteen females and 16 males participated in this study. Data from the female participants have previously been reported (Khuu et al., 2016). Participants had to be between 18 and 50 years old, free of back or lower extremity pain lasting more than 2 weeks within the last 2 months, and deny a history of lower extremity or back surgery to be included in the study. All participants provided written informed consent prior to participation. This study was approved by Boston University's Institutional Review Board.

2.3. Instrumentation

Kinematic data were collected using a 10-camera motion capture system (Nexus, Vicon Motion Systems Ltd., Oxford, UK). Ground reaction force data were recorded using the force plates in a split-belt instrumented treadmill (Bertec Corporation, Columbus, OH). Kinematic and ground reaction force data were acquired at 100 Hz and 1000 Hz, respectively.

2.4. Procedures

Participants wore a form-fitting shirt, spandex shorts, and their own exercise shoes. Reflective markers were placed bilaterally on the trunk, pelvis, and lower extremity as previously described (Lewis, Foch, Luko, Loverro, & Khuu, 2015) by a single tester (AK). A static standing calibration trial was collected for each participant following marker placement to create a participant-specific model. Anatomical markers on the medial knees and ankles were removed after the calibration trial to allow for freer movement.

Each participant performed 3 SLS tasks on each leg. For all 3 tasks, participants stood on the instrumented treadmill with each

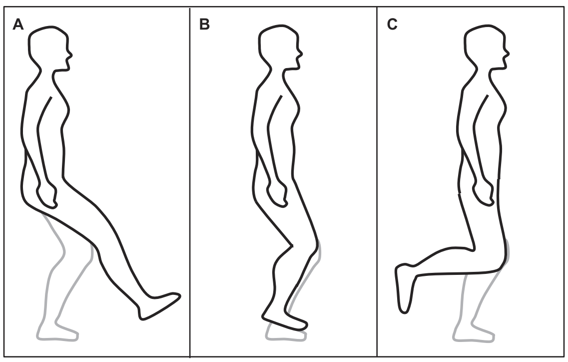

Fig. 1. Each participant performed 3 single leg squat (SLS) tasks: (A) SLS-Front, (B) SLS-Middle, and (C) SLS-Back. The tasks were differentiated by the position of the non-stance leg.

foot on an individual force plate with their arms by or out to their sides. They shifted their weight onto 1 leg and held their non-stance leg in 1 of 3 positions (Fig. 1). The positions were (1) the non-stance leg extended out anteriorly (SLS-Front) (Crossley, Zhang, Schache, Bryant, & Cowan, 2011), (2) the non-stance knee slightly flexed and the non-stance foot held in line with the ankle of the stance leg (SLS-Middle), and (3) the non-stance knee in 90° of flexion while keeping the non-stance thigh vertical (SLS-Back) (Graci et al., 2012). These positions represent a range of the positions used in both research and clinical practice. Participants were instructed to squat at low as possible in a controlled manner and return to the starting position with both feet on the ground. Each task was demonstrated and participants had an opportunity to practice the task. Participants were provided with verbal feedback to help them perform the tasks in a smooth, fluid motion at a consistent speed. Each task was performed 5 times on each leg. A trial was recollected or excluded if the performance was affected by loss of balance, incorrect non-stance leg position, or jerky or non-continuous movement. The order of the tasks was randomized. The right leg was tested first for each task out of convenience.

2.5. Data processing

Kinematic marker data were labeled using Vicon Nexus (Version 1.8.5) and processed in Visual3D (C-Motion, Inc., Germantown, MD) as previously described (Lewis et al., 2015). These data were filtered using a low-pass, fourth-order Butterworth filter with a cutoff frequency of 6 Hz (Robertson & Dowling, 2003). Angular data were calculated using a Visual3D hybrid model with a CODA pelvis (Bell, Brand, & Pedersen, 1989) and a right-handed Cardan X-Y-Z rotation sequence (mediolateral, anteroposterior, vertical) (Cole, Nigg, Ronsky, & Yeadon, 1993). Hip, knee, and ankle joint angles were calculated as the angle between the distal and proximal segments. The lab coordinate system was used to define the trunk and pelvic segment angles. Ground reaction force data were filtered using a low-pass, fourth-order Butterworth filter with a cutoff frequency of 10 Hz (Robertson & Dowling, 2003). Kinematic marker positions and ground reaction force data were used to calculate internal joint moments. Custom code (MATLAB, The MathWorks, Inc., Natick, MA) was used to extract trunk and pelvic segment angles, hip, knee, and ankle joint angles, and hip, knee, and ankle moments when the stance leg first reached 60° of knee flexion (60KF) as well as at peak knee flexion (PKF). Reaching at least 60° of knee flexion is a suggested criterion for a "good" single leg squat (Crossley et al., 2011). Analyzing at 60KF allows for comparison at a point common for all squat tasks and participants. Analyzing at PKF compares participants at the deepest point of the squat, which may be different across squat tasks and participants. Additionally, these analysis points are common in existing literature for single leg tasks (Graci et al., 2012; Lewis et al., 2015).

2.6. Statistical analysis

Statistical analysis was performed with SPSS software (Version 20.0, IBM Corporation, Armonk, NY). The variables of interest were trunk, pelvic, hip, knee, and ankle angles as well as hip, knee, and ankle moments in the sagittal and frontal planes at 60KF and PKF. Joint moments were normalized to body mass prior to analysis. Differences between sexes and SLS tasks were analyzed using a linear regression model with a generalized estimating equations (GEE) correction with 1 between-subject factor (sex: females and males), 2 within-subject factors (task: SLS-Front, SLS-Middle, and SLS-Back; side of stance leg: left and right), and 1 interaction factor (sex-by-task) in the model. A separate GEE analysis was performed for each variable of interest. If a main effect of sex, task, or sex-by-task interaction was found, least significant difference (LSD) pairwise comparisons were performed. While side was included in the model to account for the inclusion of both legs, side-to-side asymmetry was not the focus of this study and therefore not analyzed. Statistical significance for all tests was set at $P < 0.05$.

3. Results

Females and males were not significantly different in terms of age (mean ± standard deviation, 23.1 ± 1.9 vs. 22.2 ± 3.7 years) and body mass index (23.2 ± 2.6 vs. 23.6 ± 2.2 kg/m^2), although males were taller (1.65 ± 0.08 vs. 1.81 ± 0.08 m) and had greater mass (63.1 ± 8.0 vs. 77.7 ± 11.4 kg) than females ($P < 0.001$).

Kinematic differences between sexes and tasks were noted for multiple segments across the SLS tasks at 60KF (Table 1) and PKF (Table 2) with interactions of sex and task noted for the pelvis and hip (Figs. 2 and 4). For kinetic variables, task differences were noted at both analysis points while the only sex difference was knee extension moment at PKF. There were interactions of sex and task for kinetic variables at the hip at PKF and at the knee at 60KF (Figs. 3 and 5).

3.1. Interaction of sex and task

Significant interactions of sex and task were noted for anterior pelvic tilt (P = 0.038), hip flexion angle (P = 0.033), and hip abduction moment (P = 0.046) at PKF (Fig. 6). There were also significant interactions for knee extension moment (P = 0.028) and knee adduction moment (P = 0.021) at 60KF (Fig. 7). Anterior pelvic tilt at PKF was least during SLS-Front, followed by SLS-Middle, and the greatest during SLS-Back ($P < 0.001$) for both females and males. Females were in more anterior pelvic tilt than males for ($P \le 0.021$), but the magnitude of difference between sexes was greatest for the SLS-Front ($P < 0.001$) and least for the SLS-Back ($P = 0.021$).

Similar to anterior pelvic tilt, hip flexion at PKF was least during SLS-Front, followed by SLS-Middle, and greatest during SLS-Back ($P < 0.001$) in both females and males. Although pairwise comparisons did not reveal significant differences, the hip flexion exhibited by females and males at PKF was less similar during SLS-Front ($P = 0.135$) and became more similar in SLS-Middle

Table 1
Kinematic and kinetic variables (mean ± SD) at 60° of knee flexion (60KF) for each single leg squat (SLS) task for females and males.

	Females			Males		
Variable at 60KF	SLS-Front	SLS-Middle	SLS-Back	SLS-Front	SLS-Middle	SLS-Back
Joint angle (°)						
Trunk flexion[†]	13.0 ± 9.2	19.5 ± 11.6	18.4 ± 11.2	10.6 ± 7.4	17.9 ± 10.2	15.6 ± 8.1
Trunk ipsilateral flexion[*,†]	1.4 ± 2.2	1.7 ± 2.4	2.3 ± 2.2	3.4 ± 2.7	3.5 ± 2.4	4.9 ± 2.7
Pelvic anterior tilt[*,†]	6.6 ± 8.4	17.0 ± 9.0	24.2 ± 9.2	−4.3 ± 6.0	8.6 ± 8.1	16.7 ± 8.1
Pelvic hike[*,†]	3.7 ± 2.1	2.1 ± 1.9	−2.3 ± 3.6	4.3 ± 3.1	3.0 ± 3.9	0.0 ± 3.6
Hip flexion[*,†]	35.5 ± 11.1	47.7 ± 12.7	53.1 ± 11.9	26.2 ± 7.5	41.2 ± 10.6	47.4 ± 9.8
Hip adduction[*,†]	5.8 ± 4.3	6.4 ± 3.3	10.6 ± 5.2	1.3 ± 4.6	2.6 ± 5.9	6.4 ± 5.8
Knee abduction[†]	8.2 ± 6.3	7.9 ± 6.5	7.2 ± 6.5	7.1 ± 6.0	6.0 ± 5.8	5.0 ± 6.0
Ankle dorsiflexion[†]	24.5 ± 5.2	23.5 ± 5.5	25.4 ± 5.0	23.3 ± 4.0	21.2 ± 4.8	23.1 ± 3.8
Ankle eversion[†]	9.3 ± 3.7	8.8 ± 3.0	9.4 ± 3.6	9.8 ± 3.2	10.0 ± 3.1	10.1 ± 3.3
Normalized joint moment (Nm/kg)						
Hip extension[†]	0.63 ± 0.33	0.73 ± 0.42	0.48 ± 0.32	0.47 ± 0.23	0.70 ± 0.37	0.44 ± 0.31
Hip abduction	0.79 ± 0.15	0.76 ± 0.16	0.76 ± 0.14	0.74 ± 0.14	0.76 ± 0.16	0.75 ± 0.15
Knee extension[‡]	1.20 ± 0.21	1.25 ± 0.23	1.38 ± 0.20	1.37 ± 0.21	1.32 ± 0.18	1.45 ± 0.17
Knee adduction[‡]	0.09 ± 0.19	0.08 ± 0.20	0.09 ± 0.23	0.08 ± 0.19	0.02 ± 0.18	0.04 ± 0.19
Ankle plantar flexion[†]	0.61 ± 0.20	0.48 ± 0.22	0.47 ± 0.23	0.62 ± 0.18	0.53 ± 0.20	0.51 ± 0.16
Ankle inversion[†]	0.27 ± 0.10	0.24 ± 0.08	0.24 ± 0.08	0.22 ± 0.07	0.20 ± 0.08	0.20 ± 0.06

* Significant main effect of sex from a linear regression model with a generalized estimating equations (GEE) correction ($P < 0.05$).
† Significant main effect of task from a linear regression model with a GEE correction ($P < 0.05$).
‡ Significant sex-by-task interaction from a linear regression model with a GEE correction ($P < 0.05$).

Table 2
Kinematic and kinetic variables (mean ± SD) at peak knee flexion (PKF) for each single leg squat (SLS) task for females and males.

	Females			Males		
Variable at PKF	SLS-Front	SLS-Middle	SLS-Back	SLS-Front	SLS-Middle	SLS-Back
Joint angle (°)						
Trunk flexion[†]	18.8 ± 11.5	24.4 ± 13.6	23.5 ± 12.4	18.6 ± 14.5	24.0 ± 15.2	22.5 ± 10.8
Trunk ipsilateral flexion[*,†]	0.9 ± 2.6	1.6 ± 2.7	2.3 ± 2.1	3.3 ± 4.4	3.5 ± 3.1	4.7 ± 2.8
Pelvic anterior tilt[‡]	5.6 ± 9.2	17.5 ± 8.4	27.1 ± 9.1	−7.3 ± 7.4	8.2 ± 9.1	20.1 ± 8.6
Pelvic hike[†]	2.9 ± 2.8	1.1 ± 3.0	−5.6 ± 3.4	3.5 ± 3.8	1.4 ± 4.3	−4.1 ± 4.3
Hip flexion[‡]	47.7 ± 13.5	59.9 ± 15.1	65.8 ± 12.1	40.8 ± 13.4	56.4 ± 13.7	65.8 ± 11.4
Hip adduction[*,†]	10.3 ± 5.2	11.2 ± 3.9	15.6 ± 5.1	4.0 ± 5.5	5.8 ± 6.5	10.7 ± 6.6
Knee flexion[*,†]	82.6 ± 5.7	78.6 ± 8.2	74.9 ± 5.7	87.5 ± 13.2	84.0 ± 9.3	81.9 ± 7.5
Knee abduction[†]	8.8 ± 7.0	7.8 ± 7.1	6.0 ± 7.4	6.7 ± 7.1	5.2 ± 6.5	2.9 ± 6.5
Ankle dorsiflexion[†]	30.9 ± 5.8	28.6 ± 5.9	29.4 ± 5.7	29.9 ± 5.7	27.6 ± 6.4	28.4 ± 5.7
Ankle eversion	10.6 ± 4.5	10.1 ± 3.8	10.1 ± 4.4	11.7 ± 3.8	11.7 ± 3.5	11.6 ± 3.5
Normalized joint moment (Nm/kg)						
Hip extension[†]	1.04 ± 0.41	1.10 ± 0.52	0.84 ± 0.39	1.06 ± 0.68	1.21 ± 0.62	1.00 ± 0.48
Hip abduction[‡]	0.93 ± 0.17	0.89 ± 0.16	0.87 ± 0.15	0.82 ± 0.19	0.83 ± 0.18	0.85 ± 0.20
Knee extension[*,†]	1.59 ± 0.26	1.56 ± 0.28	1.64 ± 0.24	1.92 ± 0.29	1.78 ± 0.25	1.86 ± 0.23
Knee adduction[†]	0.26 ± 0.23	0.20 ± 0.25	0.16 ± 0.27	0.31 ± 0.28	0.19 ± 0.25	0.14 ± 0.25
Ankle plantar flexion[†]	0.82 ± 0.23	0.63 ± 0.27	0.62 ± 0.27	0.93 ± 0.28	0.77 ± 0.33	0.77 ± 0.31
Ankle inversion[†]	0.34 ± 0.13	0.29 ± 0.11	0.29 ± 0.11	0.33 ± 0.11	0.29 ± 0.10	0.29 ± 0.10

* Significant main effect of sex from a linear regression model with a generalized estimating equations (GEE) correction ($P < 0.05$).
† Significant main effect of task from a linear regression model with a GEE correction ($P < 0.05$).
‡ Significant sex-by-task interaction from a linear regression model with a GEE correction ($P < 0.05$).

($P = 0.475$) and SLS-Back ($P = 0.898$).

Hip abduction moment at PKF in females was greater during SLS-Front than both SLS-Middle ($P = 0.044$) and SLS-Back ($P = 0.003$), although not different in males ($P \geq 0.299$). Females had a greater hip abduction moment at PKF than males during SLS-Front ($P = 0.015$), but similar hip abduction moments to males during SLS-Middle ($P = 0.192$) and SLS-Back ($P = 0.518$).

At 60KF, both females and males had a greater knee extension moment in SLS-Back compared to SLS-Front and SLS-Middle ($P \leq 0.001$). Females, however, demonstrated a smaller knee extension moment than males during SLS-Front at 60KF ($P = 0.015$) despite no difference during SLS-Middle ($P = 0.279$) and SLS-Back ($P = 0.215$). For the knee adduction moment at 60KF, females had a similar moment across tasks ($P \geq 0.459$), but males demonstrated a greater knee adduction moment during SLS-Front than SLS-Middle ($P < 0.001$) and SLS-Back ($P = 0.019$).

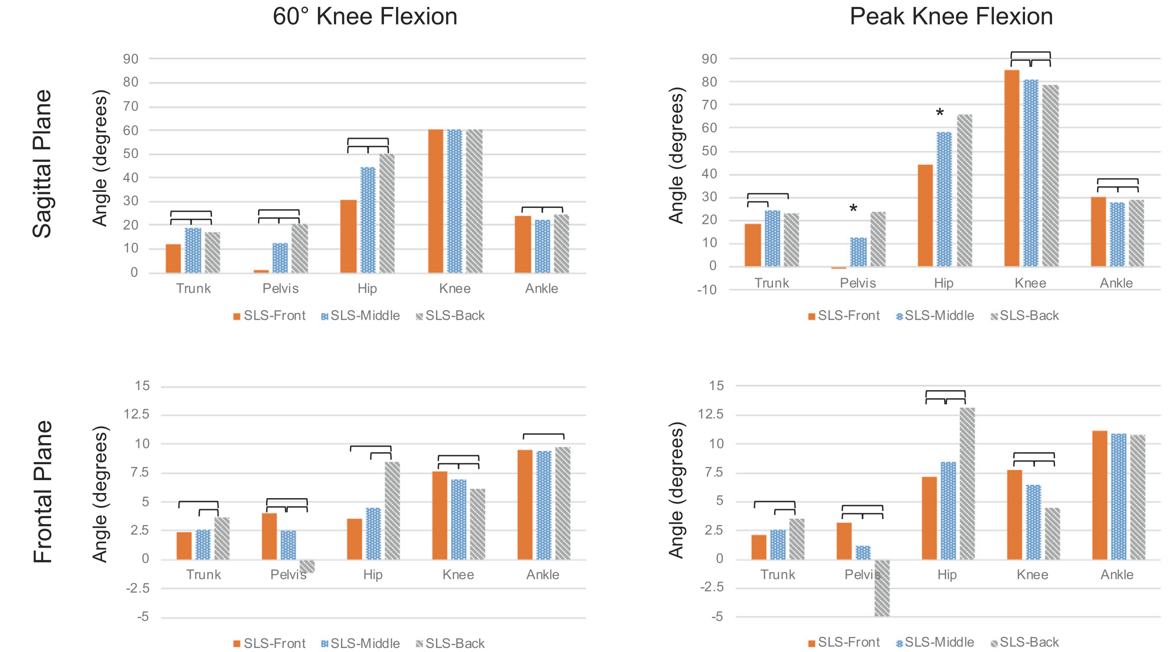

Fig. 2. Mean kinematic variables in the sagittal and frontal planes at 60° of knee flexion and at peak knee flexion for the three tasks. * Indicate significant sex-by-task interactions; brackets indicate significant pairwise comparisons following a significant main effect of task.

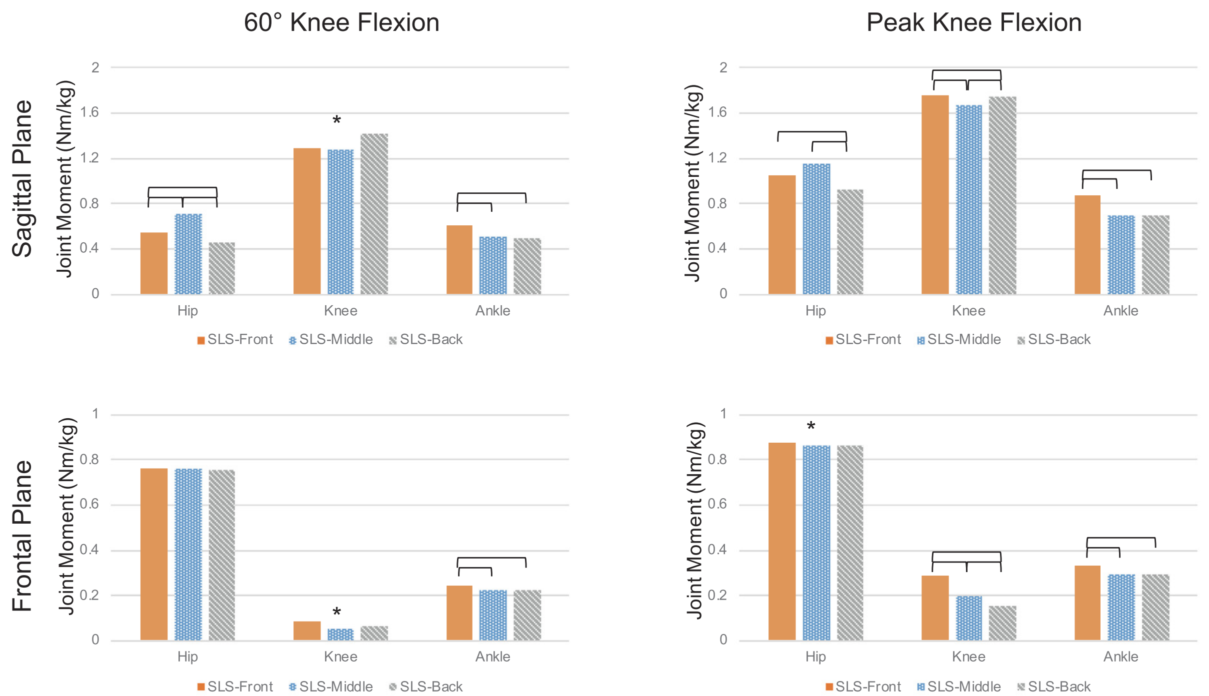

Fig. 3. Mean kinetic variables in the sagittal and frontal planes at 60° of knee flexion and at peak knee flexion for the three tasks. * Indicate significant sex-by-task interactions; brackets indicate significant pairwise comparisons following a significant main effect of task.

3.2. Sex differences

At 60KF, there were sex differences for ipsilateral trunk flexion, pelvic tilt and hike, and hip flexion and adduction angles. Females were in 2.2° less ipsilateral trunk flexion ($P < 0.001$), 9.0° more anterior pelvic tilt ($P = 0.001$), 1.3° less contralateral pelvic hike ($P = 0.032$), 7.2° more hip flexion ($P = 0.036$), and 4.1° more hip adduction ($P < 0.001$) at 60KF compared to males.

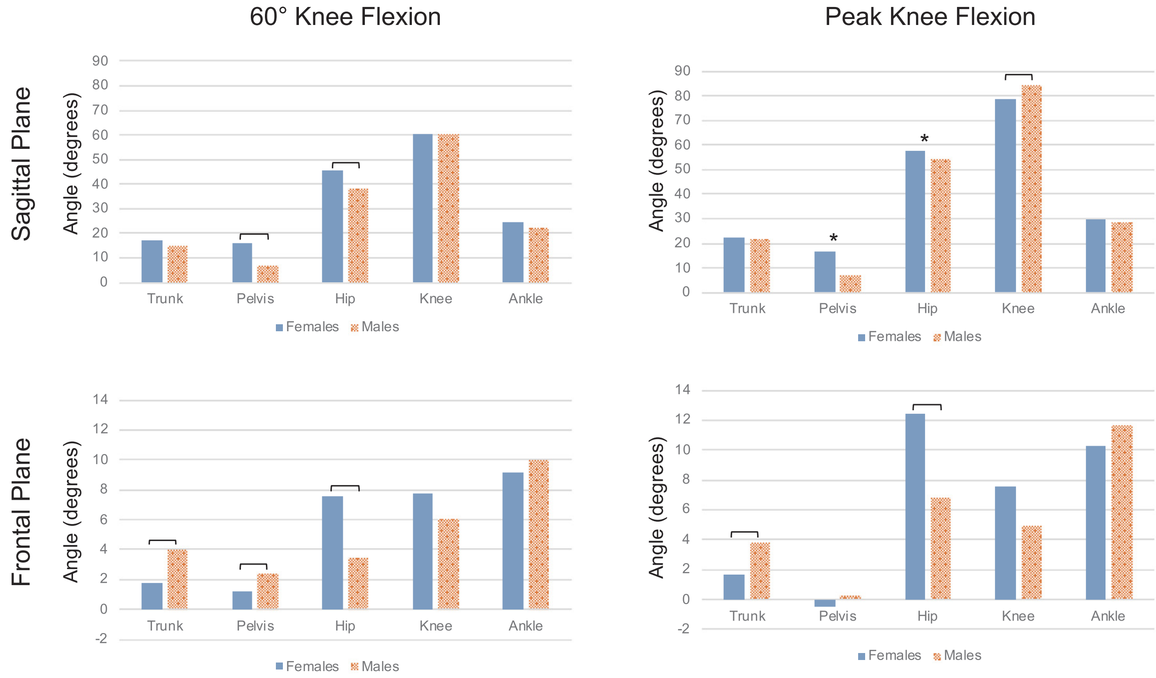

Fig. 4. Mean kinematic variables in the sagittal and frontal planes at 60° of knee flexion and at peak knee flexion for females and males. * Indicate significant sex-by-task interactions; brackets indicate significant pairwise comparisons following a significant main effect of sex.

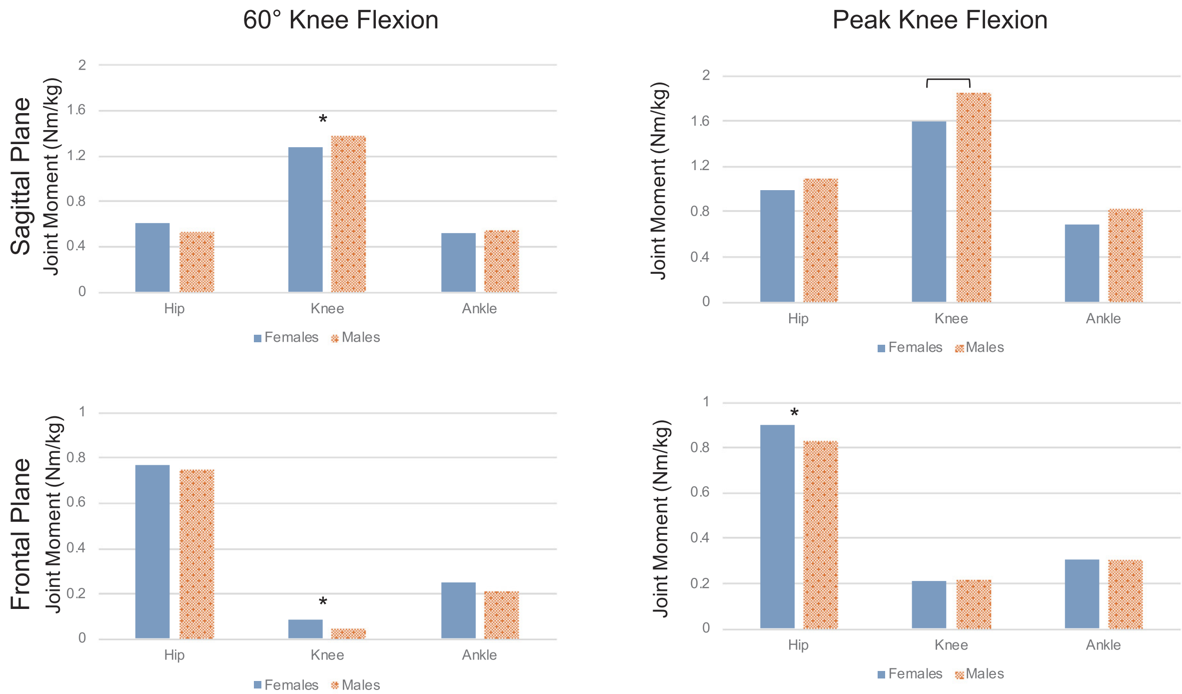

Fig. 5. Mean kinetic variables in the sagittal and frontal planes at 60° of knee flexion and at peak knee flexion for females and males. * Indicate significant sex-by-task interactions; brackets indicate significant pairwise comparisons following a significant main effect of sex.

At PKF, there were sex differences for ipsilateral trunk flexion, hip adduction, and knee flexion angles and for knee extension moment. Females were in 2.2° less ipsilateral trunk flexion ($P < 0.001$), 5.5° more hip adduction ($P < 0.001$), and 5.7° less knee flexion ($P = 0.018$) compared to males at PKF. Females also had a knee extension moment that was 0.255 Nm/kg lower than males ($P = 0.001$).

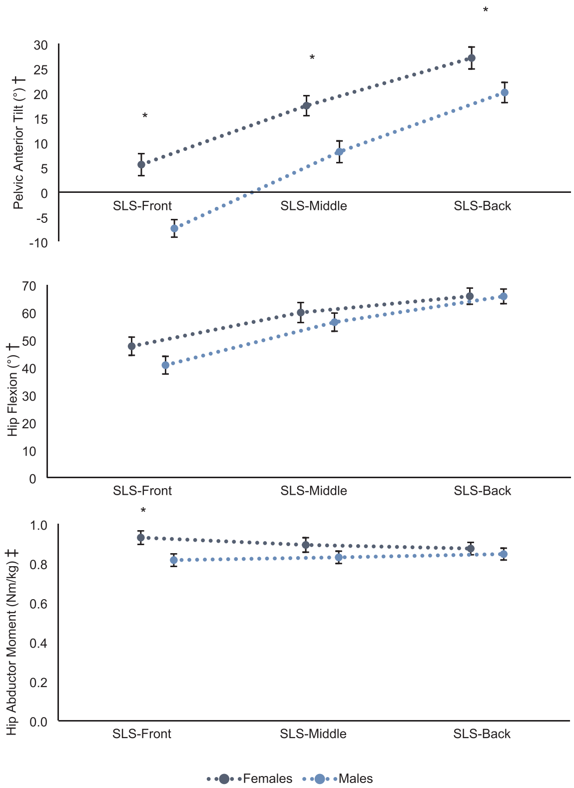

Fig. 6. Means ± standard errors of pelvic anterior tilt angle, hip flexion angle, and hip abduction moment at peak knee flexion for females and males for each single leg squat (SLS) task. A significant sex-by-task interaction was observed for each variable. *Significant difference between females and males for the SLS task ($P < 0.05$). †Significant differences between all SLS tasks for females and males ($P < 0.001$). ‡Significant differences between SLS-Front and both SLS-Middle and SLS-Back for females ($P < 0.05$).

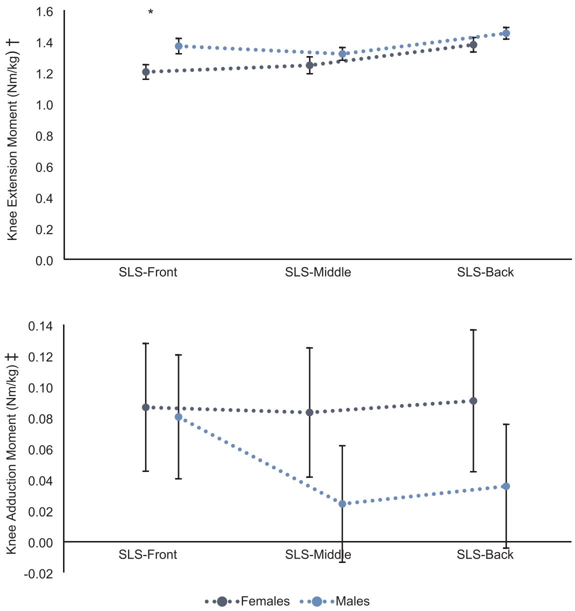

Fig. 7. Means ± standard errors of knee extension moment and knee adduction moment at 60° of knee flexion for females and males for each single leg squat (SLS) task. A significant sex-by-task interaction was observed for each variable. *Significant difference between females and males for the SLS task ($P < 0.05$). †Significant differences between SLS-Back and both SLS-Front and SLS-Middle for females and males ($P \leq 0.001$). ‡Significant differences between SLS-Front and both SLS-Middle and SLS-Back for males ($P < 0.05$).

3.3. Task differences

There were task differences in kinematic variables at both analysis points for trunk flexion, trunk ipsilateral flexion, contralateral pelvic hike, hip adduction, knee abduction, and ankle dorsiflexion angles. Hip flexion and ankle eversion angles were different between tasks at 60KF. Knee flexion and ankle eversion angles were also different at PKF. At 60KF, the trunk was in less flexion (5.2°, $P < 0.001$) and less ipsilateral flexion (1.2°, $P < 0.001$), and the pelvis was hiked more (5.2°, $P < 0.001$) in the SLS-Front than in the SLS-Back. The hip was less flexed (19.4°, $P < 0.001$) and less adducted (4.9°, $P < 0.001$), while the knee was more abducted (1.6°, $P < 0.001$) and the ankle was less everted (0.2°, $P = 0.046$) in the SLS-Front than in the SLS-Back. The angles for SLS-Middle were in between SLS-Front and SLS-Back for pelvic hike ($P \leq 0.001$), hip flexion ($P < 0.001$), and knee abduction ($P \leq 0.039$). Trunk flexion was greater for SLS-Middle than both SLS-Front (6.9°, $P < 0.001$) or SLS-Back (1.7°, $P = 0.034$). SLS-Middle had less trunk ipsilateral flexion (1.5°, $P < 0.001$) and less hip adduction (4.0°, $P < 0.001$) than SLS-Back, but was not different from SLS-Front for either variable ($P \geq 0.057$). Ankle dorsiflexion for SLS-Middle was less than both SLS-Front (1.5°, $P < 0.001$) and SLS-Back (1.9°, $P < 0.001$).

At PKF, there was more pelvic hike (8.0°, $P < 0.001$), knee flexion (6.6°, $P < 0.001$), knee abduction (3.3°, $P < 0.001$), and ankle dorsiflexion (1.5°, $P < 0.001$) in the SLS-Front than in the SLS-Back. There was also less trunk flexion (4.3°, $P = 0.003$), trunk ipsilateral flexion (1.4°, $P < 0.002$), and hip adduction (6.0°, $P < 0.001$) in the SLS-Front than in the SLS-Back. The values for SLS-Middle were in between SLS-Front and SLS-Back for pelvic hike, hip adduction, knee flexion and abduction, as well as knee abduction moment. There was less ankle dorsiflexion at PKF for SLS-Middle than for either SLS-Front or SLS-Back (2.3°, $P < 0.001$ and 0.8°, $P = 0.010$, respectively). There was more trunk flexion in SLS-Middle than SLS-Front (5.5°, $P < 0.001$) and less ipsilateral trunk flexion in SLS-Middle than SLS-Back (1.0°, $P < 0.001$).

For kinetics, there were also task differences at both analysis points for hip extension moment and ankle plantar flexion and inversion moments**.** Knee extension and abduction moments were also different at PKF. At 60KF, the moments were also greater for hip extension (0.09Nm/kg, $P = 0.007$) and ankle plantar flexion and inversion (0.12 Nm/kg, $P < 0.001$, and 0.02 Nm/kg, $P = 0.002$, respectively) in the SLS-Front than in the SLS-Back. For SLS-Middle, the hip extension moment was greater than both SLS-Front (0.17Nm/kg, $P < 0.001$) and SLS-Back (0.26Nm/kg, $P < 0.001$). The ankle plantar flexion moment and inversion moments were less for SLS-Middle than SLS-Front (0.11Nm/kg and 0.02Nm/kg, $P < 0.001$), but were not different from SLS-Back ($P \geq 0.289$). At PKF, there were higher moments for knee extension (0.13Nm/kg, $P = 0.017$), knee adduction (0.014Nm/kg, $P < 0.001$), ankle plantar flexion (0.18Nm/kg, $P < 0.001$), and ankle inversion (0.04, $P < 0.001$) for the SLS-Front compared to the SLS-Back. Knee adduction moment was different between tasks ($P \leq 0.003$): SLS-Front had the greatest knee adduction moment, SLS-Back had the smallest, and SLS-Middle was in-between. The hip extension moment for SLS-Middle was greater than for SLS-Back (0.24Nm/kg, $P < 0.001$), and the knee extension moment for SLS-Middle was less than either SLS-Front or SLS-Back (0.08 Nm/kg, $P = 0.006$ and 0.07 Nm/kg, $P < 0.001$, respectively). The ankle plantar flexion and inversion moments were less for SLS-Middle than for SLS-Front (0.18 Nm/kg, $P < 0.001$ and 0.04 Nm/kg, $P < 0.001$, respectively).

4. Discussion

Females and males respond differently to altering the position of the non-stance leg during the SLS as demonstrated by the sex-by-task interactions for kinematic variables at the pelvis and hip and for kinetic variables at the hip and knee. For each of these variables, differences between females and males were more apparent during the SLS-Front than during the SLS with the other two non-stance leg positions. Thus, sex differences during the SLS may be accentuated with the non-stance leg anterior. For the kinematic variables (anterior pelvic tilt and hip flexion), males were more affected by non-stance leg position than were females. This was not true for the kinetic variables. While males demonstrated similar hip abduction moments between the SLS tasks at PKF, females had a greater hip abduction moment during SLS-Front than both SLS-Middle and SLS-Back. Conversely, females demonstrated similar knee adduction moments across the 3 SLS tasks while males displayed a greater knee adduction moment during SLS-Front than both SLS-Middle and SLS-Back at 60KF.

Different movement patterns at the trunk, pelvis, hip, and knee as well as differences in joint moments at the hip and knee across the 3 SLS tasks tests were observed between females and males. Our kinematic results at the hip and knee were fairly consistent with those reported by previous studies. That is, females displayed greater hip flexion (Zeller et al., 2003) and hip adduction (Graci et al., 2012; Zeller et al., 2003) and less knee flexion (Graci et al., 2012) than males. However, unlike previous findings, females in this study did not perform the SLS with greater knee abduction and less trunk flexion (Graci et al., 2012) than males. Although the data suggest that females were in greater knee abduction compared to males across tasks, the difference was not significant at either analysis point. Females and males did have additional differences in ipsilateral trunk flexion and anterior pelvic tilt in this study. The small sex-difference with females in 2.2° less ipsilateral trunk flexion than males may not be clinically important. The larger difference noted in pelvic tilt may be due to differences in data processing between studies as we do not assume that the pelvis is in 0^0 of tilt in initial standing; therefore, the increased anterior pelvic tilt in females compared to males may be due to differences in standing posture.

Noting the position of the non-stance leg during the SLS is important when clinically evaluating the trunk, pelvis, and lower extremity as it influences what movement pattern is observed. While we found small differences for ipsilateral trunk flexion, knee abduction, and ankle dorsiflexion demonstrated, the differences between SLS-Front and SLS-Back for trunk flexion, pelvic tilt and hike, and hip flexion and adduction were nearly 5° or more suggesting that they may be clinically observable. Our results showed that participants performed SLS-Front with less trunk, pelvic, and hip motion and more knee flexion compared to the other SLS tasks.

Therefore, if a clinician is assessing a patient for indicators of poor SLS performance (e.g., more trunk, pelvic, and hip motion and less knee flexion) (Crossley et al., 2011), they would want to perform the SLS with the non-stance leg in the middle or back position. The clinician may be less likely to notice a poor SLS performance when the non-stance leg is in the front position. Additionally, while clinicians often focus on frontal plane motion of the knee during the SLS, we noted larger differences at the hip and pelvis, highlighting the importance of looking throughout the kinetic chain.

When the SLS is used as an exercise, clinicians may be better able to target or avoid specific movements or muscles by using different non-stance leg positions. For example, the SLS-Front may be more appropriate initially for an individual with femoroacetabular impingement (FAI) syndrome, as pain is often provoked with hip flexion and adduction (Ganz et al., 2003). However, progressing the individual to the SLS-Back may be important for function as it requires asymmetrical leg movement with one hip flexing while the other remains in neutral.

Researchers using the SLS also need to be aware that different non-stance leg positions during the task can have consequential effects on their participants' kinematics and kinetics. As such, they should include a description of the non-stance leg position in their task procedures and be cautious when interpreting results across studies with different SLS variations (Warner et al., 2019).

There were limitations to this study. The participants were young adults with no back or lower extremity pain. Thus, we do not know if our findings generalize beyond a young, healthy population. Since participants performed both the SLS on both their right and their left leg, we analyzed both sides, but did not consider leg dominance in our analyses nor did we randomize which side was collected first. There may have been order effects or differences between the performances on the dominant leg and those on the non-dominant leg. Another limitation of this study is the lack of muscle strength and electromyography measures. These additional measures may help with the interpretation of our findings and elucidate if muscle weakness or different muscle activation levels are related to our observed differences.

5. Conclusion

Females and males exhibited different kinematics at the trunk, pelvis, and lower extremity and kinetics at the hip and knee during the 3 SLS tasks with different non-stance leg positions. These findings highlight the importance of considering the position of the non-stance leg when using the SLS in research and clinical evaluation. Clinicians may use these findings to better inform their selection among the 3 SLS tasks to best meet the individual goals of their patients.

Ethical approval

This study was approved by Boston University's Institutional Review Board. Informed consent was obtained from all participants in this study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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