The effects of symmetric and asymmetric foot placements on sit-to-stand joint moments

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Abstract

The purpose of this study was to determine the effects of symmetric and asymmetric foot placements on joint moments during sit-to-stand movements. Three symmetric (foot-neutral, foot-back, and foot-intermediate) and three asymmetric foot placements (preferred stagger, nonpreferred stagger, and intermediate stagger) were tested. Standard (46cm) and low (41cm) seat heights were chosen to represent an average public seat height and a 10% lower seat height. Using inverse dynamics, maximum ankle plantarflexion, knee extension, hip extension, and hip abduction moments were calculated. Hip extension moments were significantly increased when using foot-neutral as compared to foot-back. Ankle plantarflexion and knee extension moments were significantly increased when a foot was placed in the posterior position as compared to the anterior position for preferred and nonpreferred stagger. Knee extension moments were significantly increased at the low seat height as compared to the standard seat height. When shifting the feet anterior or posterior for symmetric placements during sit-to-stand, the most dramatic effect was an increase in hip extension moments when the feet are shifted anteriorly. Utilizing asymmetric foot placements during sit-to-stand produced increases in ankle plantarflexion and knee extension moments for the posteriorly placed limb, with reductions in the anteriorly placed limb.
Introduction

The capability to move from a sitting to a standing position is essential for mobility and is associated with independent living. Researchers have analyzed joint moments for clinical populations that may find sit-to-stand movements to be challenging, including older adults, those with total joint replacements, females during pregnancy, and obese individuals. Older adults who were able to complete sit-to-stand without arm assistance generated higher knee extension moments than older adults who required armrest support [1]. In contrast, individuals after total knee arthroplasty utilized higher hip extension moments than controls during sit-to-stand [2,3], along with higher knee and hip extension moments in the uninvolved limb than in the operated limb [4]. Pregnant females produced higher knee extension moments and lower hip extension moments for sit-to-stand during the third trimester as compared to the first trimester [5]. Similarly, obese individuals demonstrated higher knee extension moments and lower hip extension moments during sit-to-stand than controls [6]. It is often difficult to explain whether differences in sit-to-stand joint moments for these clinical groups are due to strength deficits [7,8], balance compensations [9], and/or changes in movement strategy [10].

Distribution of joint moments between the ankles, knees, hips, and/or between limbs can be manipulated by different movement strategies or by varied techniques such as alternative foot placements for sit-to-stand movements. At a particular seat height, symmetrical foot placements can be adjusted by moving both feet to a more anterior position (reduced knee flexion) or a more posterior position (increased knee flexion). Foot placements with reduced knee flexion have resulted in higher hip extension moments during sit-to-stand [11-13]. In contrast, foot placements with increased knee flexion have resulted in higher ankle plantarflexion moments [14]. At a particular stance width, asymmetric foot placements can be utilized by placing one
foot more anterior and one foot more posterior relative to the other. Placing the foot of an affected limb posterior to the foot of the unaffected limb has been suggested to preferentially load the affected limb for patients with hemiparesis or hemiplegia [15,16]. However, the effect of asymmetric foot placements on the joint moments of the anteriorly and posteriorly placed limbs during sit-to-stand is not well established.

In order for a sit-to-stand foot placement to be utilized at home and in public places, it must be functional over a range of seat heights and must not disrupt balance. Lower seat heights have been reported to be challenging for functionally impaired older adults [1,7,17], females in the third trimester of pregnancy [5], and patients after total knee arthroplasty [2]. In general, lower seat heights have been associated with the requirements to generate higher knee extension moments [1,13,18] and to a lesser extent, higher hip extension moments [13,18]. While sagittal plane joint moments give an indication of functional strength requirements, practical foot placements must also provide stable balance in the frontal plane. Center of pressure parameters [16], loading symmetry between limbs [19-21], and hip abduction joint moments can be useful measures of mediolateral balance and strength requirements associated with a foot placement. Mediolateral balance and strength are of particular concern when suggesting the utilization of asymmetric foot placements for sit-to-stand movements.

The purpose of this study was to determine the effects of symmetric and asymmetric foot placements on joint moments during sit-to-stand movements. Consistent with previous findings, our first hypothesis was that hip extension moments would increase with the feet placed more anterior and that ankle plantarflexion moments would increase with the feet placed more posterior during symmetric foot placements. Considering preferential limb loading, our second hypothesis was that knee extension moments would increase in the limb placed in the more
posterior position during asymmetric foot placements. Also consistent with previous findings, our third hypothesis was that knee extension and hip extension moments would increase at a lower seat height. However, we did not expect there to be any interaction between foot placement and seat height, thus meaning that the effect of a lower seat height would be similar across foot placements. The long-term goal is to understand how foot placement can be used during sit-to-stand movements to either reduce loading for joint protection or to preferentially increase loading for targeted neuromuscular rehabilitation.

Methods

Twenty-three individuals (gender 4 male/19 female, age 22±1 year, height 1.70±0.07 m, mass 66±13 kg) participated in this study. Each participant provided informed consent as approved by the Xxxx Xxxxx Xxxxxxxxxx Institutional Review Board prior to data collection. Exclusion criteria included any neurological or musculoskeletal disorders that would affect the research participant’s ability to perform sit-to-stand movements.

Three symmetric foot placements were tested: foot-neutral, foot-back, and foot-intermediate. Foot-neutral was positioned with the ankle joints under the knee joints, foot-back with the toes under the knee joints, and foot-intermediate with the midfeet under the knee joints. In addition, three asymmetric foot placements were tested: preferred stagger (preferred toes under knee joint, nonpreferred ankle joint under knee joint), nonpreferred stagger (nonpreferred toes under knee joint, preferred ankle joint under knee joint), and intermediate stagger (preferred toes under knee joint, nonpreferred midfoot under knee joint). The preferred limb was determined by asking which leg the participant felt more stable on during single leg standing, which is considered a sensitive balance measure that is also associated with risk of falling [22]. Participants were
allowed to self-select a constant foot placement width, anterior-posterior foot positions were
individually set according to the foot placement definitions, seat depth was set at 75% of thigh
length, and the movement was completed with arms folded across the chest to eliminate
differences in upper body momentum generation. Participants were instructed to start with their
back straight and to perform the sit-to-stand using their regular, smooth pattern of movement.
Standard (46cm) and low (41cm) seat heights were chosen to represent an average public seat
height and a 10% lower seat height. The seated surface had no back support. In total, each
participant completed 2 repetitions of 12 conditions (6 foot placements x 2 seat heights). The
order of the trials was randomized to reduce potential effects of learning and fatigue.

Twenty reflective markers were tracked during the sit-to-stand movements by an eight-
camera motion analysis system (Vicon Nexus, Los Angeles, CA). The dynamic marker set
included bilateral great toes, lateral midfeet, lateral malleoli, anterior shins, lateral knee joint
lines, anterior thighs, greater trochanters, posterior superior iliac spines, and acromion processes,
along with single markers on the sacrum and cervicale. Eight additional markers (bilateral heels,
medial malleoli, medial knee joint lines, and anterior superior iliac spines) were recreated using
transformations determined from a static standing trial. Participants placed each foot on a
separate in-ground force platform (AMTI, Watertown, MA), and foot placements were indicated
on the platforms using colored tape to ensure trial-to-trial reproducibility. The video and force
platform data were collected at 160Hz, and noise was reduced with a fourth-order, low-pass
Butterworth filter at a cutoff frequency of 6Hz.

Sit-to-stand movements were analyzed from elevation onset to vertical stabilization as
determined from the combined preferred and nonpreferred leg vertical ground reaction forces.
Elevation onset was detected at the initial point where the combined vertical ground reaction
forces equaled body weight, which occurs just prior to seat-off [23]. Vertical stabilization was defined at the point where the combined vertical ground reaction forces returned to body weight after first overshooting body weight, then dipping under body weight (acceleration, then deceleration of the center of mass). Lower extremity masses, center of mass positions, joint center positions, and moments of inertia were individually estimated [24,25]. Using inverse dynamics, preferred and nonpreferred maximum ankle plantarflexion, knee extension, hip extension, and hip abduction moments were calculated, transformed to the distal segment coordinate system, and normalized by body mass [26]. Anterior-posterior (A/P) and medial-lateral (M/L) center of pressure (COP) excursions were calculated as the difference between maximal and minimal COP positions. Mean A/P and M/L COP velocities were calculated by using the first central difference method and averaging across the duration of the sit-to-stand movement. Symmetry measures were calculated using the maximum values from the preferred and nonpreferred legs during the sit-to-stand movement (adapted from [20]):

\[
\% \text{Symmetry} = 100 - \frac{100 \times \text{abs}(\text{preferred}_{\text{max}} - \text{nonpreferred}_{\text{max}})}{\text{preferred}_{\text{max}} + \text{nonpreferred}_{\text{max}}}
\]

Weight-bearing symmetry was calculated using vertical ground reaction forces and joint loading symmetry values were calculated using joint moments. All calculations were determined using Matlab (Natick, MA) and were averaged across the two repetitions of each condition.

Multivariate ANOVA was used to test for main effects of foot placement, seat height, and their interactions (SPSS, Chicago, IL). Separate multivariate ANOVAs were performed for maximum joint moments, COP parameters, and symmetry measures with significance levels defined as \(p<0.05\). When significant main effects were found, post-hoc Scheffe comparisons were utilized for foot placement effects and univariate ANOVA for seat height effects. The Scheffe and univariate ANOVA comparisons were Bonferroni adjusted by the number of
potentially dependent variables: 8 for joint moment comparisons (p<0.006), 4 for COP parameter comparisons (p<0.013), and 5 for symmetry measure comparisons (p<0.01).

Results

Maximum joint moments were dependent upon foot placement and seat height (p<0.001), but not their interaction (p=0.990). Preferred ankle plantarflexion moments (Fig. 1) were significantly increased when using preferred stagger as compared to nonpreferred stagger and foot-intermediate (p≤0.001). In addition, preferred ankle plantarflexion moments increased with intermediate stagger and foot-back as compared to nonpreferred stagger (p≤0.001). Nonpreferred ankle plantarflexion moments increased when using nonpreferred stagger as compared to preferred stagger, intermediate stagger, and foot-intermediate (p<0.001). Ankle plantarflexion moments increased 78% when comparing the posterior to anterior position for preferred and nonpreferred stagger.

Preferred knee extension moments (Fig. 2) were significantly increased when using preferred stagger as compared to nonpreferred stagger, foot-neutral, and foot-intermediate (p≤0.001). In addition, preferred knee extension moments increased when using intermediate stagger as compared to nonpreferred stagger and foot-neutral (p<0.001). Preferred knee extension moments also increased with the three symmetric foot placements as compared to nonpreferred stagger (p≤0.001). Nonpreferred knee extension moments increased when using nonpreferred stagger as compared to all other foot placements (p≤0.001). In addition, nonpreferred knee extension moments increased with the three symmetric foot placements and intermediate stagger as compared to preferred stagger (p≤0.001). Both preferred and nonpreferred knee extension moments were significantly increased for the low seat height as compared to the standard seat.
height (p<0.001). Knee extension moments increased 66% when comparing the posterior position to anterior position for preferred and nonpreferred stagger.

Preferred hip extension moments (Fig. 3) were significantly increased when using foot-neutral as compared to foot-back, intermediate stagger, and preferred stagger (p<0.001). Nonpreferred hip extension moments increased when using foot-neutral as compared to foot-back, nonpreferred stagger, intermediate stagger, and foot-intermediate (p<0.001). In addition, nonpreferred hip extension moments increased with preferred stagger as compared to foot-back (p<0.001). Nonpreferred hip extension moments also increased for the low seat height as compared to the standard seat height (p=0.001). Hip extension moments increased 49% when comparing foot-neutral to foot-back. There were no significant differences in hip abduction moments as a function of foot placement or seat height, with values only ranging from 0.22±0.09 Nm/kg to 0.27±0.09 Nm/kg.

COP parameters were dependent upon foot placement and seat height (p≤0.004), but not their interaction (p=0.934). A/P COP excursions (Table 1) were significantly increased when using foot-neutral as compared to all other foot placements (p≤0.004). A/P COP excursions and mean A/P COP velocities increased for the low seat height as compared to the standard seat height (p≤0.010). There were no significant differences in M/L COP excursions or mean M/L COP velocities as a function of foot placement or seat height.

Symmetry measures were dependent upon foot placement and seat height (p≤0.006), but not their interaction (p=0.128). Weight bearing symmetry (Table 2) was significantly reduced when using preferred stagger as compared to the three symmetric foot placements and intermediate stagger (p≤0.007). In addition, weight bearing symmetry was reduced with nonpreferred stagger as compared to the three symmetric foot placements (p≤0.001). Ankle plantarflexion moment
symmetry was reduced when using nonpreferred stagger as compared to the three symmetric foot placements (p≤0.001). In addition, ankle plantarflexion moment symmetry was reduced with preferred stagger as compared to foot-back and foot-neutral (p≤0.004). Knee extension moment symmetry was reduced when using preferred stagger or nonpreferred stagger as compared to the three symmetric foot placements and intermediate stagger (p<0.001). Knee extension moment symmetry was also reduced for the standard seat height as compared to the low seat height (p<0.001). There were no significant differences in hip extension or hip abduction moment symmetry as a function of foot placement or seat height.

**Discussion**

The purpose of this study was to investigate how symmetric and asymmetric foot placements affect joint moments during sit-to-stand movements. Our first hypothesis was partially supported as hip extension moments significantly increased (+49%) with foot-neutral as compared to foot-back. However, ankle plantarflexion moments did not significantly increase between foot-back and foot-neutral. Instead, participants displayed modest increases in both ankle plantarflexion (+13%) and knee extension (+15%) moments for foot-back. Our second hypothesis was supported as knee extension moments significantly increased (+64%) in the posteriorly placed limb when comparing preferred and nonpreferred stagger. In addition, using intermediate stagger significantly increased preferred knee extension moments (+53%) when compared to nonpreferred stagger. Our third hypothesis was partially supported as knee extension (+11%) and nonpreferred hip extension (+8%) moments significantly increased when comparing low and standard seat heights. However, increases in preferred hip extension (+4%) moments were non-significant between the low and standard seat heights. As expected, there
were no significant interactions between foot placement and seat height, which supports that foot placement effects were similar for the low and standard seat heights.

When shifting the feet anterior or posterior for symmetric placements during sit-to-stand, the most dramatic effect was an increase in hip extension moments when using foot-neutral. The challenge of using foot-neutral was demonstrated by significantly increased A/P COP excursions as compared to all other foot placements. Since the ankle joints are aligned under the knee joints with foot-neutral, the body center of mass must travel further in the anterior direction from a seated position to the standing base of support. This increase in hip extension moments indicates that foot-neutral may be a poor choice for individuals in need of hip joint protection, such as those with hip osteoarthritis or post total hip joint replacement [11,20]. Foot-neutral may also be a poor choice during pregnancy [5,10] or for obese individuals [6], since it has been reported that these clinical groups generate lower hip extension moments. For those individuals who are unable to assume a foot-back placement due to lack of flexibility or knee joint degeneration, then foot-intermediate is a practical option to attenuate hip extension moments.

Utilizing asymmetric foot placements during sit-to-stand produced increases in ankle plantarflexion and knee extension moments for the posteriorly placed limb, with reductions in the anteriorly placed limb. Weight-bearing, ankle plantarflexion moment, and knee extension moment symmetry measures were consequently reduced with preferred and nonpreferred stagger as compared to the three symmetric foot placements. However, the observation that M/L COP excursions/velocities and hip abduction moments were not significantly increased with asymmetric foot placements is a promising indication that frontal plane balance was not disturbed in healthy individuals. Taken together, asymmetric foot placements may be an option to preferentially load the ankle and knee joints in cases such as hemiparesis [15,16] or to protect
these joints for individuals post total knee arthroplasty [2-4,21]. In addition, if an individual has developed a chronic pattern of unloading a limb during symmetric foot placements, then an asymmetric placement could potentially improve balance by increasing weight-bearing and joint loading symmetry [27]. Intermediate stagger presents an option that still increases ankle and knee loading in the posteriorly placed limb, but with less difference between limbs than preferred and nonpreferred stagger.

There are several limitations to this study that should be considered when interpreting and applying the results. One limitation was that the research participants were primarily young healthy females who occasionally stated that using foot-neutral at the low seat height was moderately difficult, but in general, were not challenged by the sit-to-stand movements. The observation that intermediate stagger was not statistically different than the three symmetric placements for the symmetry measures further supports this assertion. Individuals who have strength deficits, lower extremity pain, and/or reduced flexibility may not be able to utilize the full set of tested foot placements due to their functional limitations. In addition, the low and standard seat heights represented a practical range for public places, but the recommendation of foot placement could be affected if even lower seat heights will be encountered [7,17,28]. A second limitation was that foot placement was the only movement intervention tested in this study. Research participants in this study completed the movement with their arms folded across their chests using primarily a momentum-generation strategy. The use of arm swing momentum generation, armrest support, and different movement strategies [10,28-30] would also likely affect the distribution of joint moments during sit-to-stand.
Conflict of interest: The authors certify that they have no conflict of interest in connection with the material presented in this manuscript.

References


Table 1

The effects of foot placement and seat height on COP parameters

<table>
<thead>
<tr>
<th></th>
<th>COP Excursions (cm) and Mean Velocities (cm/s)</th>
<th>A/P COP Excursion</th>
<th>M/L COP Excursion</th>
<th>A/P COP Velocity</th>
<th>M/L COP Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td></td>
<td>5.9 ± 2.1</td>
<td>3.6 ± 1.5</td>
<td>7.7 ± 2.8</td>
<td>6.5 ± 2.9</td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td>6.7 ± 2.3</td>
<td>3.8 ± 1.7</td>
<td>8.7 ± 3.3a</td>
<td>6.7 ± 3.1</td>
</tr>
<tr>
<td>Foot-back</td>
<td></td>
<td>5.2 ± 2.0</td>
<td>3.2 ± 1.0</td>
<td>7.4 ± 2.5</td>
<td>6.1 ± 2.6</td>
</tr>
<tr>
<td>Foot-intermediate</td>
<td></td>
<td>6.1 ± 1.8</td>
<td>3.5 ± 1.5</td>
<td>7.9 ± 3.0</td>
<td>6.3 ± 3.0</td>
</tr>
<tr>
<td>Foot-neutral</td>
<td></td>
<td>8.3 ± 2.1</td>
<td>3.7 ± 1.6</td>
<td>9.6 ± 3.8</td>
<td>6.3 ± 2.8</td>
</tr>
<tr>
<td>Preferred stagger</td>
<td></td>
<td>6.5 ± 2.2</td>
<td>4.3 ± 2.0</td>
<td>8.3 ± 3.0</td>
<td>7.1 ± 3.3</td>
</tr>
<tr>
<td>Intermediate stagger</td>
<td></td>
<td>5.4 ± 1.6</td>
<td>3.5 ± 1.3</td>
<td>7.7 ± 2.7</td>
<td>6.5 ± 2.6</td>
</tr>
<tr>
<td>Nonpreferred stagger</td>
<td></td>
<td>6.1 ± 2.2</td>
<td>4.1 ± 1.7</td>
<td>8.2 ± 2.9</td>
<td>7.3 ± 3.7</td>
</tr>
</tbody>
</table>

Significantly greater than (p<0.010): a standard height, c foot-back, d foot-intermediate, f preferred stagger, g intermediate stagger, h nonpreferred stagger
Table 2

The effects of foot placement and seat height on vertical ground reaction and joint moment symmetry measures

<table>
<thead>
<tr>
<th>Symmetry (%)</th>
<th>Weight Bearing</th>
<th>Ankle Plantarflex</th>
<th>Knee Extension</th>
<th>Hip Extension</th>
<th>Hip Abduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>93 ± 5</td>
<td>74 ± 21</td>
<td>84 ± 14&lt;sup&gt;b&lt;/sup&gt;</td>
<td>87 ± 9</td>
<td>79 ± 18</td>
</tr>
<tr>
<td>Low</td>
<td>93 ± 4</td>
<td>75 ± 20</td>
<td>88 ± 10</td>
<td>87 ± 9</td>
<td>79 ± 18</td>
</tr>
<tr>
<td>Foot-back</td>
<td>95 ± 3</td>
<td>84 ± 12</td>
<td>93 ± 4</td>
<td>88 ± 8</td>
<td>80 ± 19</td>
</tr>
<tr>
<td>Foot-intermediate</td>
<td>95 ± 3</td>
<td>79 ± 19</td>
<td>94 ± 3</td>
<td>89 ± 6</td>
<td>81 ± 18</td>
</tr>
<tr>
<td>Foot-neutral</td>
<td>95 ± 3</td>
<td>83 ± 16</td>
<td>92 ± 5</td>
<td>89 ± 8</td>
<td>81 ± 16</td>
</tr>
<tr>
<td>Preferred stagger</td>
<td>90 ± 6&lt;sup&gt;cde&lt;/sup&gt;</td>
<td>66 ± 20&lt;sup&gt;ce&lt;/sup&gt;</td>
<td>73 ± 12&lt;sup&gt;cde&lt;/sup&gt;</td>
<td>85 ± 10</td>
<td>79 ± 17</td>
</tr>
<tr>
<td>Intermediate stagger</td>
<td>93 ± 4</td>
<td>73 ± 21</td>
<td>88 ± 6</td>
<td>86 ± 9</td>
<td>78 ± 21</td>
</tr>
<tr>
<td>Nonpreferred stagger</td>
<td>91 ± 5&lt;sup&gt;cde&lt;/sup&gt;</td>
<td>61 ± 24&lt;sup&gt;cde&lt;/sup&gt;</td>
<td>74 ± 13&lt;sup&gt;cde&lt;/sup&gt;</td>
<td>84 ± 9</td>
<td>77 ± 19</td>
</tr>
</tbody>
</table>

Significantly less than (p≤0.007): <sup>b</sup> low height, <sup>c</sup> foot-back, <sup>d</sup> foot-intermediate, <sup>e</sup> foot-neutral, <sup>g</sup> intermediate stagger
Fig. 1. The effects of foot placement and seat height on maximum ankle plantarflexion moments. 
Significantly greater than (p≤0.001): $d$ foot-intermediate, $f$ preferred stagger, $g$ intermediate stagger, $h$ nonpreferred stagger.

Fig. 2. The effects of foot placement and seat height on maximum knee extension moments. 
Significantly greater than (p≤0.001): $a$ standard height, $c$ foot-back, $d$ foot-intermediate, $e$ foot-neutral, $f$ preferred stagger, $g$ intermediate stagger, $h$ nonpreferred stagger.

Fig. 3. The effects of foot placement and seat height on maximum hip extension moments. 
Significantly greater than (p≤0.001): $a$ standard height, $c$ foot-back, $d$ foot-intermediate, $f$ preferred stagger, $g$ intermediate stagger, $h$ nonpreferred stagger.