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Age and initial position affect movement biomechanics in sit to walk transitions: Lower limb muscle activity and joint moments

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A B S T R A C T

Facilitating forward movement while maintaining dynamic stability during transitions like sit-to-walk (STW) requires coordination from many muscles. Age-related muscle, sensory, and neural decline can introduce compensatory biomechanics when completing STW, such as adjusting initial foot position or rising with arm support. Many previous STW studies restrict arm movement and prescribe symmetric foot positions, therefore the purpose of this study was to quantify lower limb muscle excitations and joint moments in STW transitions from four initial foot positions [symmetric, posterior offset, wide, narrow] and two arm placements [hands on knees, arms folded] in 15 younger and 15 older adults. Peak knee and ankle joint extension moments, as well as peak electromyography of five bilateral lower-limb muscles were analyzed. In all conditions, older adults had larger knee extension moments, whereas younger adults had larger ankle plantarflexion moments. Older adults generated larger peak excitation from the knee extensor muscles during rising compared to younger adults, consistent with the higher knee extension moments. Older adults had greater peak dorsiflexor and plantarflexor muscle excitation while rising compared to younger adults. Posterior offset and wide foot positions required the largest peak ankle plantarflexion and knee extension moments and plantarflexor muscle excitation. Arm-supported rising decreased peak knee extensor muscle excitation. In addition, there were interaction effects between age and initial foot position/arm placement for multiple quantities, indicating that the effects of foot and arm placement vary with age. These results inform assessments of movement performance and guidelines for rising given individual lower limb capability.

1. Introduction

Muscle, joint, sensory, and neurological decline are common in aging, reducing the ability to generate the forces and accelerations necessary to complete everyday movement tasks (e.g., van der Kruk, et al., 2021). More than half of all injurious falls occur while performing common transitional tasks such as walking, rising from a chair, or transferring between both (Ooi, et al., 2021; Pengpid and Peltzer, 2018), referred to as sit-to-walk (STW). Transitional movements like STW merge rising and walking, and thus require coordination and strength from the knee extensor and plantarflexor muscle groups to rise and accelerate the whole-body center of mass (COM) upward and forward, which have been shown during sit-to-stand (STS, Caruthers, et al., 2016) and walking (Neptune, et al., 2001). As STW transitions are critical for daily living, clinical professionals frequently use STW to assess balance performance and fitness in older adults. However, often only the duration or the ability to perform the STW movement is assessed (Nnodim and Yung, 2015). Studying the underlying lower-limb biomechanics of the STW movement is important to improve clinical balance assessments and prevent falls in movement transitions.

STW merges rising and gait into one continuous motion and can be achieved through various strategies (Buckley, et al., 2009). Different initial foot and arm placements individuals use to merge tasks have varying neuromusculoskeletal demands. For example, rising during STS with one foot posterior to the other can induce a dominant vertical rise strategy, which causes the knee joint to extend before the trunk and hip. This strategy requires the knee extensor muscles to move the body COM upward, and suggests the need for ankle plantarflexor muscles on the offset limb to move the body COM upward and forward (Kawagoe, et al., 2000). In addition, arm-supported rising from armrests during STS requires lower knee and hip moments as well as knee extensor muscle excitation (Burdett, et al., 1985; Arborelius, et al., 1992; Seedhom and Terayama, 1976). A study that investigated preferred STS strategies found that healthy older participants frequently used their arms: 20% pushed off from an arm rest and 60% pushed off from their knees (Dolecka, et al., 2015). Previous studies have shown that initial foot position and arm placement during STS require differing musculoskeletal demands independently. However, little research has investigated biomechanics of different foot and arm placements and their potential interactions during STW, even though these placements are common in

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daily life. There is thus a need for a systematic, within-participant, biomechanical comparison of initial foot position and arm support on biomechanics in STW, when rising and gait are merged.

STW presents biomechanical challenges for older adults who have a lower neuromusculoskeletal capacity compared to younger adults (van der Kruk, et al., 2021). With reduced musculoskeletal capacity, older adults perform daily activities with compensatory movements. For example, older adults have greater hip muscle excitation than younger adults during walking (Schmitz, et al., 2009), static postural control (Amiridis, et al., 2003), and other dynamic tasks like STS (Dos Santos, et al., 2021). In addition, static and dynamic balance studies have found that older adults have greater co-contraction of the ankle dorsiflexors and plantarflexors to anticipate mechanical perturbations and increase ankle joint stiffness, decreasing the magnitude of body COM deviations (Warnica, et al., 2014; Segal, et al., 2023). However, there is little research showing if older adults use these movement strategies in STW, especially as experimental protocols often limit potential movement compensations by restricting initial foot and arm placements. Thus, evaluating age alongside initial foot and arm conditions is also needed to quantify the muscle and joint mechanics of compensatory movements across the lifespan.

The purpose of this study was to quantify the biomechanical effects of initial foot positions and arm-supported rising on lower limb muscle excitation and joint moments during STW for younger and older adults. We examined peak ankle plantarflexion and knee extension joint moments, as well as the peak linear envelope values of muscle excitation for the gastrocnemius (GAS), soleus (SOL), tibialis anterior (TA), rectus femoris (RF), and vastus lateralis (VAS). We hypothesized that older adults would generate larger knee moments and knee extensor muscle excitation during STW, consistent with prior literature indicating greater knee extension moments (Buddhadev, et al., 2020) and knee extensor muscle excitation (Schmitz, et al., 2009) in older adults during walking. We also hypothesized that rising from a posteriorly offset foot condition would result in greater knee extensor muscle excitation and larger knee extension moments from that offset limb. We expected rising with arm support (i.e., push off from the knees) to reduce knee extensor muscle excitation and knee extension moments during rising. Lastly, we hypothesized that older adults would have smaller ankle plantarflexion moments and greater muscle excitation from TA, GAS, and SOL given prior evidence of reduced plantarflexion moments (Boyer, et al., 2017) and greater excitation from these muscles during walking (Schmitz, et al., 2009). The findings from this study have potential to guide clinical evaluations and movement training of older adults during transitional movements.

2. Methods

2.1. Participants

Thirty healthy younger (7M/8F, 24.26 ± 4.41 yrs, 159.4 ± 29.1 lbs, 1.73 ± 0.10 m) and older adults (5M/10F, 62.24 ± 6.62 yrs, 182.1 ± 50.2lbs, 1.69 ± 0.11 m) provided their informed consent to participate in the protocol approved by the Colorado Multiple Institutional Review Board. Participants self-reported that they did not have neurological disorders or musculoskeletal injury in the last six months. Recruited younger adults were between 18 and 35 years and older adults were between 50 and 79 years. Participants were excluded if they were taking medications that could cause dizziness or affect balance, as well as significantly impaired vision or verbal communication.

2.2. Experimental protocol

As part of a larger study, each participant completed a lateral preference survey (Coren, 1993), functional tasks of squats, heel raises, and toe ups, a standing static calibration trial, as well as 24 self-paced STW trials. All participants were right hand and foot dominant. GRFs were acquired using four in-ground force plates (AMTI, Watertown, MA, 2000 Hz) synchronized with 3D motion capture data from a seven-camera system (Qualisys, Göteborg, Sweden, 200 Hz) tracking 74 retroreflective markers (Fig. 1). Ten surface electromyography (EMG) sensors (Delsys, Boston, MA; contact material, 99.9% Ag; electrode dimensions, 5x1 mm; inter-electrode distance, 10 mm) recorded excitations from the bilateral rectus femoris, vastus lateralis, gastrocnemius, soleus, and tibialis anterior (Konrad, 2005; Perotto, 2011).

Each STW trial began seated on a stool, without shoes, with socks, and beginning in one of four initial foot positions: symmetric, offset, wide, and narrow. In the symmetric position, participants sat with their hips and knees flexed at 90°, set with a manual goniometer. The anterior/posterior (A/P) offset position shifted the dominant foot backward 2/3 foot length. In the wide position, each limb shifted outward from the symmetric position the width of the foot. In the narrow position the medial borders of the feet touched. Two arm placements were tested for each foot condition: arms folded across the chest and arms supported with hands on knees. Three trials of each randomized foot and arm placement combination were completed (Fig. 2).

2.3. Data Analysis

Kinematic marker trajectories and GRF data were processed with a bidirectional 4th-order lowpass Butterworth filter ($f_C = 6$ Hz). EMG data were digitally filtered with a 4th-order bandpass Butterworth filter (20–500 Hz), full wave rectified, and lowpass filtered ($f_C = 6$ Hz) (De Luca, 2010). STW events of start, seat off, toe off, and end were defined to isolate the phases of rising and stepping (Fig. 2). Joint moment and EMG data were analyzed from the instant of body COM movement until the stepping foot left the second force plate. EMG signals were normalized in magnitude by dividing each instant of the filtered signal by the mean peak value of the similarly processed signal for tasks that isolated the TA, GAS, SOL, RF, and VAS (Sousa and Tavares, 2012). These functional dynamic tasks included: (a) toe ups (TA), (b) heel raises (GAS, SOL), (c) and squats (RF, VAS).

A 12-segment dynamic model was developed from each participant's static calibration trial (Visual3D, C-Motion Inc, Kingston, ON), including a lumped head-torso, pelvis, thighs, shanks, feet, upper arms, and forearms. Segment geometries were defined as cylinders (trunk and pelvis), and cone frusta (other segments) (Dempster and Aitkens, 1995, Hanavan, 1964). Internal joint moments in the sagittal plane were resolved in the proximal segment's coordinate system. Both ankle and knee joint moments were normalized by body mass.

2.4. Statistical Analysis

A three-factor, mixed model ANOVA ($\alpha = 0.05$) was used to compare peak ankle plantarflexion and knee extension moments, as well as peak linear envelope values for the TA, SOL, GAS, RF, and VAS across the three main effects: age group, foot position, and arm placement (Fig. 2; Rstudio v.4.2.2, Posit, Boston, MA). When significant main or interaction effects were found for foot position, post hoc pairwise comparisons were completed using paired and unpaired t-tests with a Tukey adjustment for multiple comparisons (α=0.05). Foot position pairwise differences are reported relative to the symmetric condition. Effect size estimates were calculated using partial eta squared (η^2_p), with values of 0.01, 0.06, and 0.14 to indicate small, medium, or large effect sizes for significant/nearly significant main and interaction effects, respectively (Cohen, 1988; Richardson, 2011).

3. Results

Significant/nearly significant main and interaction effect p-values and partial eta squared effect sizes are provided in Tables 1 and 2. Significant main, interaction, and pairwise post hoc differences, alongside numerical values for each outcome metric, are detailed in

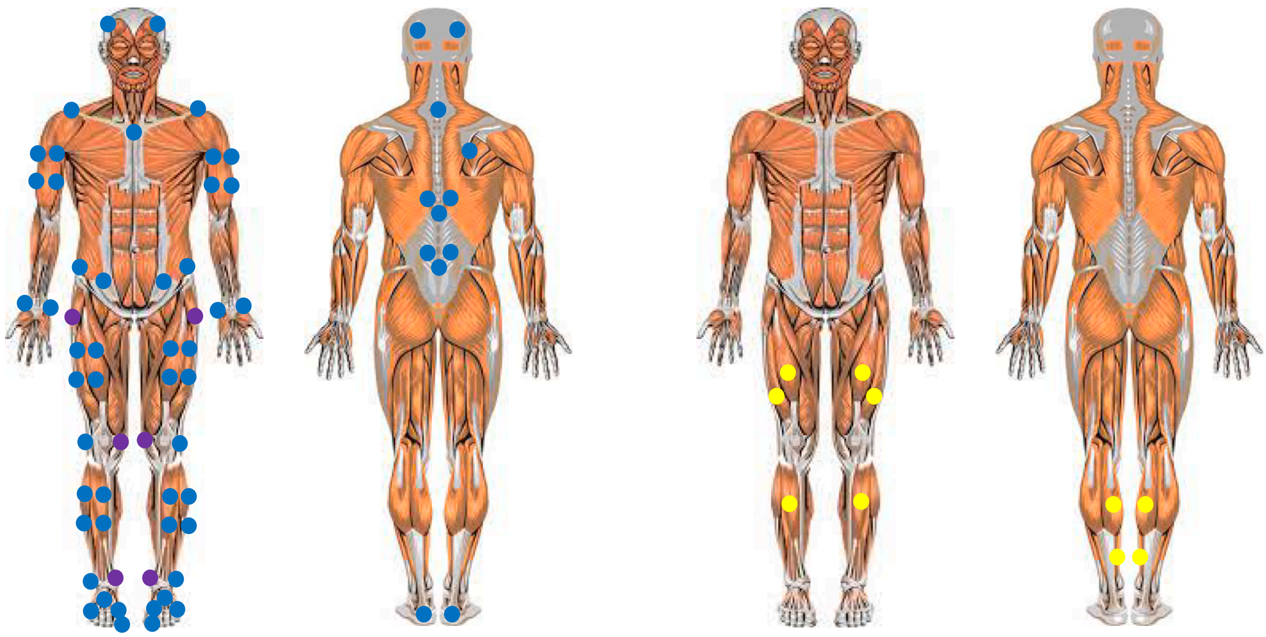

Fig. 1. Marker and electromyography sensor placement diagram. Bilateral markers included the temple, back of head, acromion, upper arm cluster, iliac crest, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), thigh cluster, shank cluster, 5th metatarsal head, 1st metatarsal head, P2 joint, dorsal foot surface, and heel. Additional markers included C7, clavicle, right back, T9-T10 marker triad, L4-L5 marker triad, medial and lateral elbow, radial wrist, and ulnar wrist. Purple markers were used for static calibration measurements only and were placed bilaterally on the greater trochanter, medial knee, and medial malleolus. Bilateral surface electromyography sensor placement included the rectus femoris, vastus lateralis, medial gastrocnemius, soleus, and tibialis anterior. (Figure modified from Konrad, 2005). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Supplementary Tables S1-S7.

3.1. Ankle plantarflexion moments

Peak ankle joint moments were analyzed during both the rising and stepping phase. During the rising phase, there was a significant main effect of foot position on the stepping limb ($p<0.001$; Table 1; Fig. 3 right plots), indicating that the wide position had 36.9% greater peak plantarflexion moment (post hoc $p<0.001$) and the A/P offset had 29.7% greater peak plantarflexion moment (post hoc $p<0.001$) compared to the symmetric position. The peak ankle plantarflexion moment when rising from the narrow position was not different from symmetric. A significant main effect of age on the stepping limb ($p=0.024$; Fig. 3 right plots), with older adults generating 9.8% less peak ankle plantarflexion moments than younger adults when rising. During the stepping phase of the STW task, there were no significant main or interaction effects for either limb.

3.2. Knee extension moments

There was a significant foot position main effect for peak knee extension moment on the stepping ($p<0.001$; Table 1; Fig. 4 right plots) and stance limbs, which occurred during the rising phase ($p<0.001$; Fig. 4 left plots). On the stepping limb, the A/P offset condition had 47.9% greater knee extension moments compared to the symmetric position (post hoc $p<0.001$), whereas on the stance limb, the A/P offset condition had 37.6% smaller knee extension moment compared to the symmetric position (post hoc $p<0.001$). The peak knee extension when rising from the narrow and wide positions was not different from symmetric on both limbs. There was also a significant age main effect for knee extension moment on both limbs ($p<0.001$; Fig. 4 all plots). Older adults generated 24.8% greater knee extension moments on the stepping limb and 22% greater knee extension moments on the stance limb compared to younger adults. There was a significant arm main effect for knee extension moment on the stepping limb only ($p=0.018$; Fig. 4 right plots), with arm-supported push off lowering knee extension moments by 8.4% compared to arms folded.

There was a significant interaction effect for age and foot position for the stepping limb's peak knee extension moment ($p<0.001$; Fig. 4 right plots), with older adults rising from the A/P offset condition having 32.7% greater knee extension moments compared to younger adults rising from the same position (post hoc $p<0.001$).

3.3. Knee extensor peak muscle excitation

There was a significant main effect of age for the stepping limb's peak RF excitation ($p<0.001$; Table 2; Figs. 5 and 6 right RF plots), as well as the stance limb's peak RF ($p<0.001$; Figs. 5 and 6 left RF plots) and stance limb's peak VAS ($p<0.001$; Figs. 5 and 6 left VAS plots) excitation. Younger adults generated 32.6% less peak RF excitation on their stepping limb and 33.3% less peak RF excitation on their stance limb compared to older adults. Older adults generated 17.6% greater VAS excitation on their stance limb compared to younger adults. In addition, there was a significant main effect of foot position on peak VAS excitation for both the stepping ($p<0.001$; Figs. 5 and 6 right VAS plots) and stance ($p<0.001$; Figs. 5 and 6 left VAS plots) limbs. The A/P offset position required 24% greater peak excitation from the stepping limb's VAS (post hoc $p<0.001$) and a 26.6% reduction in the stance limb's VAS excitation (post hoc $p<0.001$) compared to the symmetric position. Peak VAS excitation when rising from the narrow and wide positions was not different from the symmetric on both limbs. There was a significant arm effect on the stepping limb ($p=0.016$; Figs. 5 and 6 right VAS plots) for VAS, which indicated rising with arm-supported push off from the knees decreased peak VAS excitation by 9.5%.

There were significant interaction effects on both the stance limb RF ($p=0.024$; Figs. 5 and 6 left RF plots) and stepping limb VAS ($p=0.034$; Figs. 5 and 6 right VAS plots) for age and arm placement that indicated younger adults rising with their arms folded generated 50.6% smaller peak stance limb RF excitation and 18.0% smaller peak stepping limb VAS excitation than older adults rising from the same condition.

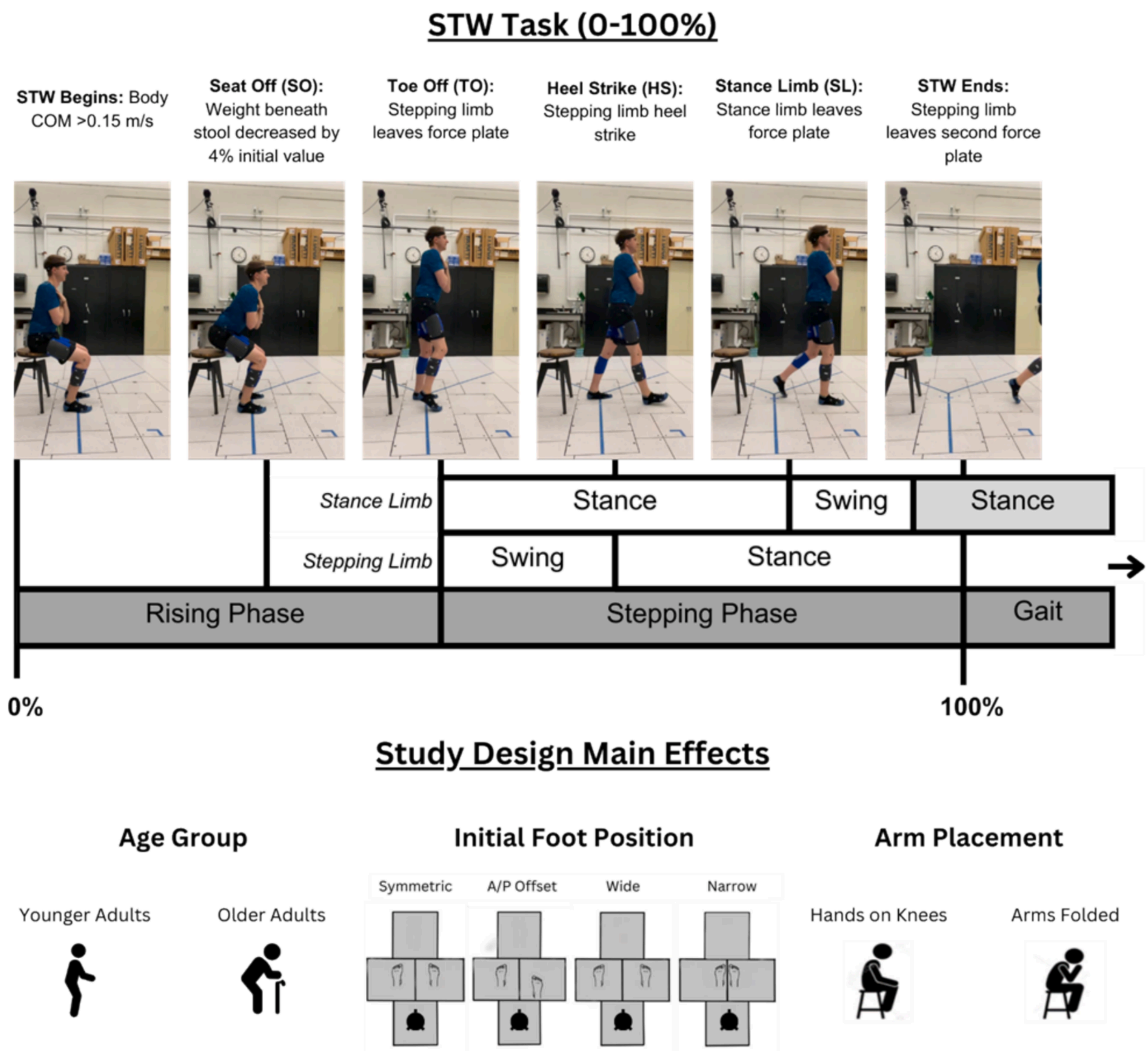

Fig. 2. STW transition phases and events (top). The beginning of the STW motion was defined as the instant the body COM velocity exceeded 0.15 m/s, adapted from Kerr et al. 2004. Seat off occurred when the weight beneath the stool decreased by 4% of its initial vertical GRF value (Kerr, et al., 2004; Kerr, et al., 2007). Toe off was the instant when the participant's stepping limb no longer contacted the force plate. The stance limb event was defined as the instant the stance limb left its respective force plate (Kerr, et al., 2004). Peak gastrocnemius and soleus muscle excitation results were analyzed during the rising and stepping phases for both stance and stepping limbs. Ankle plantarflexion and knee extension joint moments as well as peak rectus femoris, vastus lateralis, and tibialis anterior muscle excitation results were analyzed for the duration of the STW task. There is no joint moment data for the stance limb during the second stance phase as denoted by the light grey shaded box. Schematic depiction of the study's main effects (bottom), including age group (2 levels: younger and older adults), initial foot position (4 levels: symmetric, A/P offset, wide, narrow), and arm placement (2 levels: hands on knees and arms folded). Initial foot positions are defined for right foot dominance.

3.4. Rising phase shank peak muscle excitation

During the rising phase, there were significant main effects of foot position on stepping limb TA, GAS and SOL peak excitation (all $p<0.001$; Table 2, Figs. 5 and 6 right plots), as well as stance limb TA peak excitation ($p<0.001$; Figs. 5 and 6 left TA plots). For the TA, the A/P offset position required 32.4% less stepping limb excitation (post hoc $p<0.001$) and 40.8% less stance limb excitation compared to symmetric (post hoc $p < 0.001$; Figs. 5 and 6). Peak TA excitation when rising from the wide and narrow positions were not different from symmetric on both limbs. Rising from the wide position required 16.9% greater stepping limb GAS excitation (post hoc $p=0.042$) and 24.4% greater stepping limb SOL excitation (post hoc $p=0.002$) compared to the symmetric position. Peak stepping limb GAS and SOL excitation when rising from the A/P offset and narrow positions was not different from symmetric. There was also a significant age main effect for stepping limb TA ($p<0.001$; Figs. 5 and 6 right TA plots) and GAS peak excitation ($p=0.011$; Figs. 5 and 6 right GAS plots). Older adults generated 13.5% greater TA excitation, 12.0% greater GAS excitation, and trend towards more peak SOL excitation than younger adults on their stepping limb while rising.

There was a significant interaction effect between age and foot position for peak stepping limb TA ($p=0.011$; Figs. 5 and 6 right TA plots) and SOL ($p=0.042$; Figs. 5 and 6 right SOL plots) excitation. Younger adults rising from the A/P offset position had lower peak TA excitation compared to symmetric position (post hoc $p<0.001$) and older adults rising from A/P offset and wide conditions also had lower peak TA excitation compared to the symmetric position (post hoc $p<0.001$). Older adults rising from the narrow foot position had 46.0% greater peak SOL excitation compared to younger adults in the same position (post hoc $p<0.001$).

Table 1
Main effect and significant/nearly significant interaction effect (α=0.05) p-values and partial eta squared (η^2_p) effect sizes for peak ankle plantarflexion and knee extension moments. Significant main and interaction effects are bolded. * indicates an effect approached significance (0.05<p<0.10).

Outcome Metric	Age	Foot	Arms	Significant Interaction Effects
Peak Rising Phase Ankle Plantarflexion Moment				
Stepping Limb	**p=0.024** $\eta^2_{p=0.02}$	**p<0.001** $\eta^2_{p=0.33}$	p=0.890	–
Stance Limb	p=0.381	p=0.324	p=0.118	* Foot x Age (p=0.071) $\eta^2_{p=0.03}$
Peak Knee Extension Moment				
Stepping Limb	**p<0.001** $\eta^2_{p=0.19}$	**p<0.001** $\eta^2_{p=0.52}$	**p=0.018** $\eta^2_{p=0.02}$	**Foot x Age (p<0.001)** $\eta^2_{p=0.07}$
Stance Limb	**p<0.001** $\eta^2_{p=0.10}$	**p<0.001** $\eta^2_{p=0.17}$	* p=0.053 $\eta^2_{p=0.004}$	–

Table 2
Main effect and significant/nearly significant interaction effect (α = 0.05) p-values and partial eta squared (η^2_p) effect sizes for peak RF, VAS, GAS, SOL, and TA EMG signals. Significant main and interaction effects are bolded. * indicates an effect approached significance (0.05<p<0.10).

Outcome Metric	Age	Foot	Arms	Significant Interaction Effects
Peak Rectus Femoris EMG				
Stepping Limb	**p<0.001** $\eta^2_{p=0.08}$	p=0.571	p=0.329	–
Stance Limb	**p<0.001** $\eta^2_{p=0.09}$	p = 0.103	p=0.381	**Arm x Age (p=0.024)** $\eta^2_{p=0.02}$
Peak Vastus Lateralis EMG				
Stepping Limb	p=0.484	**p<0.001** $\eta^2_{p=0.10}$	**p=0.016** $\eta^2_{p=0.03}$	**Arm x Age (p=0.034)** $\eta^2_{p=0.02}$
Stance Limb	**p<0.001** $\eta^2_{p=0.05}$	**p<0.001** $\eta^2_{p=0.09}$	p=0.161	–
Peak Tibialis Anterior EMG				
Stepping Limb	**p<0.001** $\eta^2_{p=0.04}$	**p<0.001** $\eta^2_{p=0.13}$	p=0.933	–
Stance Limb	p=0.385	**p<0.001** $\eta^2_{p=0.19}$	p=0.533	**Foot x Age (p=0.011)** $\eta^2_{p=0.05}$
Peak Gastrocnemius EMG				
Rising Phase				
Stepping Limb	**p=0.011** $\eta^2_{p=0.02}$	**p<0.001** $\eta^2_{p=0.006}$	p=0.591	–
Stepping Phase				
Stepping Limb	**p<0.001** $\eta^2_{p=0.04}$	p=0.200	**p=0.048** $\eta^2_{p=0.02}$	–
Stance Limb	**p<0.001** $\eta^2_{p=0.12}$	**p<0.001** $\eta^2_{p=0.04}$	p=0.538	–
Peak Soleus EMG				
Rising Phase				
Stepping Limb	* p=0.085 $\eta^2_{p=0.01}$	**p<0.001** $\eta^2_{p=0.09}$	p=0.260	**Foot x Age (p=0.042)** $\eta^2_{p=0.04}$
Stepping Phase				
Stepping Limb	p=0.106	p=0.385	p=0.328	**Foot x Age (p<0.001)** $\eta^2_{p=0.09}$
Stance Limb	**p<0.001** $\eta^2_{p=0.05}$	p=0.430	p=0.104	–

3.5. Stepping phase shank peak muscle excitation

During the stepping phase, there was a significant foot position main effect on peak stance limb GAS excitation (p<0.001; Table 2; Figs. 5 and 6 left GAS plot) where the wide position generated 15.8% greater excitation than the narrow (post hoc p=0.038) and 18.3% greater excitation than the A/P offset condition (post hoc p=0.030). There was no difference in peak GAS excitation between the wide and symmetric positions. There was a main age effect on peak stepping limb GAS excitation (p<0.001; Figs. 5 and 6 right GAS plots), peak stance limb GAS excitation (p<0.001; Figs. 5 and 6 left GAS plots), and peak stance limb SOL (p<0.001; Figs. 5 and 6 left SOL plots). For peak GAS excitation, older adults generated 11.1% smaller excitation on their stepping limb and 18.8% smaller excitation on their stance limb compared to younger adults. Older adults generated 14.1% less peak SOL compared to younger adults. There was a significant main effect of arm placement on the stepping limb's peak GAS excitation (p=0.048; Figs. 5 and 6 right GAS plot), which indicated that rising with arm-supported push off from the knees resulted in 7.2% greater excitation compared to the arms folded condition. There were no significant main effects on peak SOL excitation for the stepping limb.

There was a significant interaction effect between foot position and age for peak stepping limb SOL excitation (p<0.001; Figs. 5 and 6 right SOL plots), with younger adults rising from the symmetric foot position with 22.6% greater peak SOL excitation compared to older adults (post hoc p=0.029).

4. Discussion

This study quantified peak lower limb joint moments and muscle

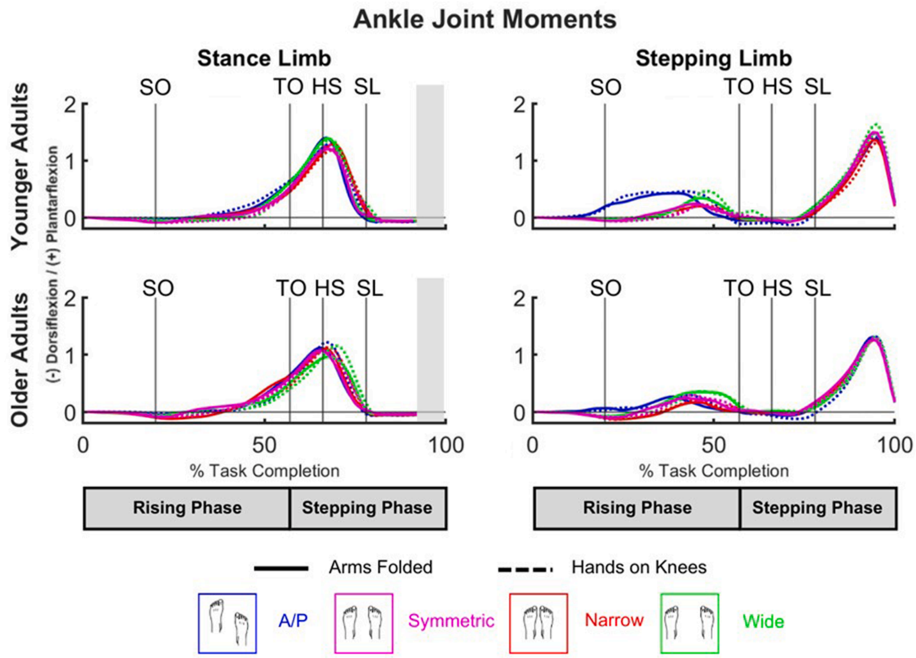

Fig. 3. Average normalized ankle plantarflexion moments (Nm/kg) for both younger and older adults in STW from each of the four initial foot positions and two arm placements. Moments were normalized by body mass. Vertical lines indicate STW (0–100%) events seat off (SO), toe-off (TO), heel strike (HS), and stance limb toe-off (SL). See Fig. 2 for full definitions of each STW event. The grey shaded region represents time when the stance limb was in contact with the ground beyond the force plate, so no data were collected. For a color version of the figure, please refer to the online version of the manuscript. Significant main, interaction, and pairwise post hoc differences are detailed in the text and numerical values are provided in Supplementary Table S1.

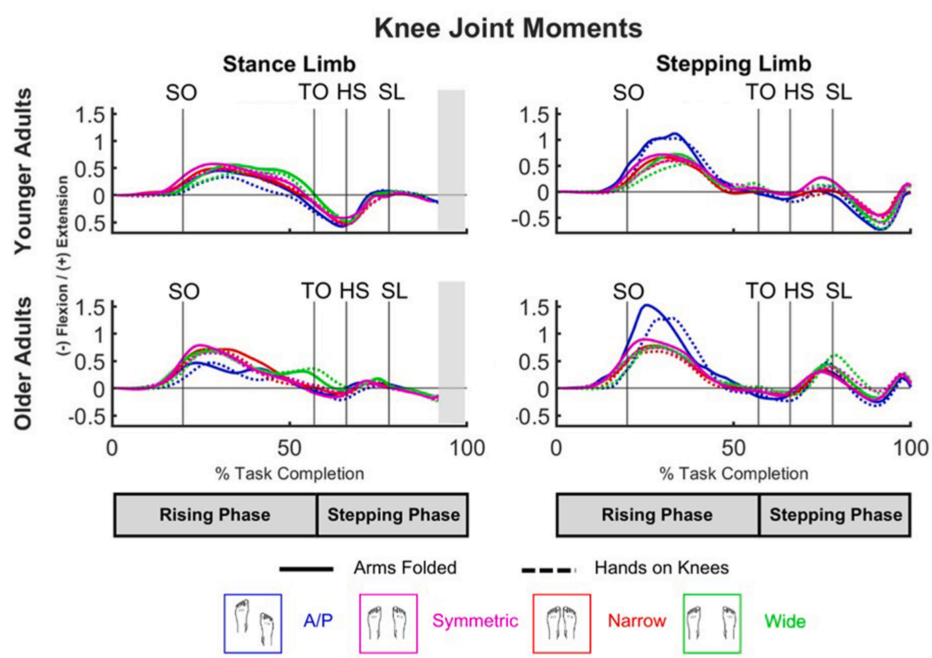

Fig. 4. Average normalized knee flexion/extension joint moments (Nm/kg) for both younger and older adults in STW from four initial foot positions and two arm placements. Moments were normalized by body mass. Vertical lines indicate STW (0–100%) events seat off (SO), toe-off (TO), heel strike (HS), and stance limb toe-off (SL). See Fig. 2 for full definitions of each STW event. The grey shaded region represents time when the stance limb was in contact with the ground beyond the force plate, so no data were collected. For a color version of the figure, please refer to the online version of the manuscript. Significant main, interaction, and pairwise post hoc differences are detailed in the text and numerical values are provided in Supplementary Table S2.

excitations of younger and older adults completing STW from four initial foot positions and two arm placements. We hypothesized that older adults would generate larger knee moments and muscle excitations, which was supported by greater peak bilateral RF and stance limb VAS excitation during the rising phase. With aging, ankle plantarflexor muscle strength is disproportionately weakened (Bok, et al., 2013) and there is greater demand for hip and knee extension moments when rising from a chair (Samuel, et al., 2013). Greater knee extension moments were also observed for older adults in this study. These joint moment and muscle excitation results indicate altered muscle recruitment in

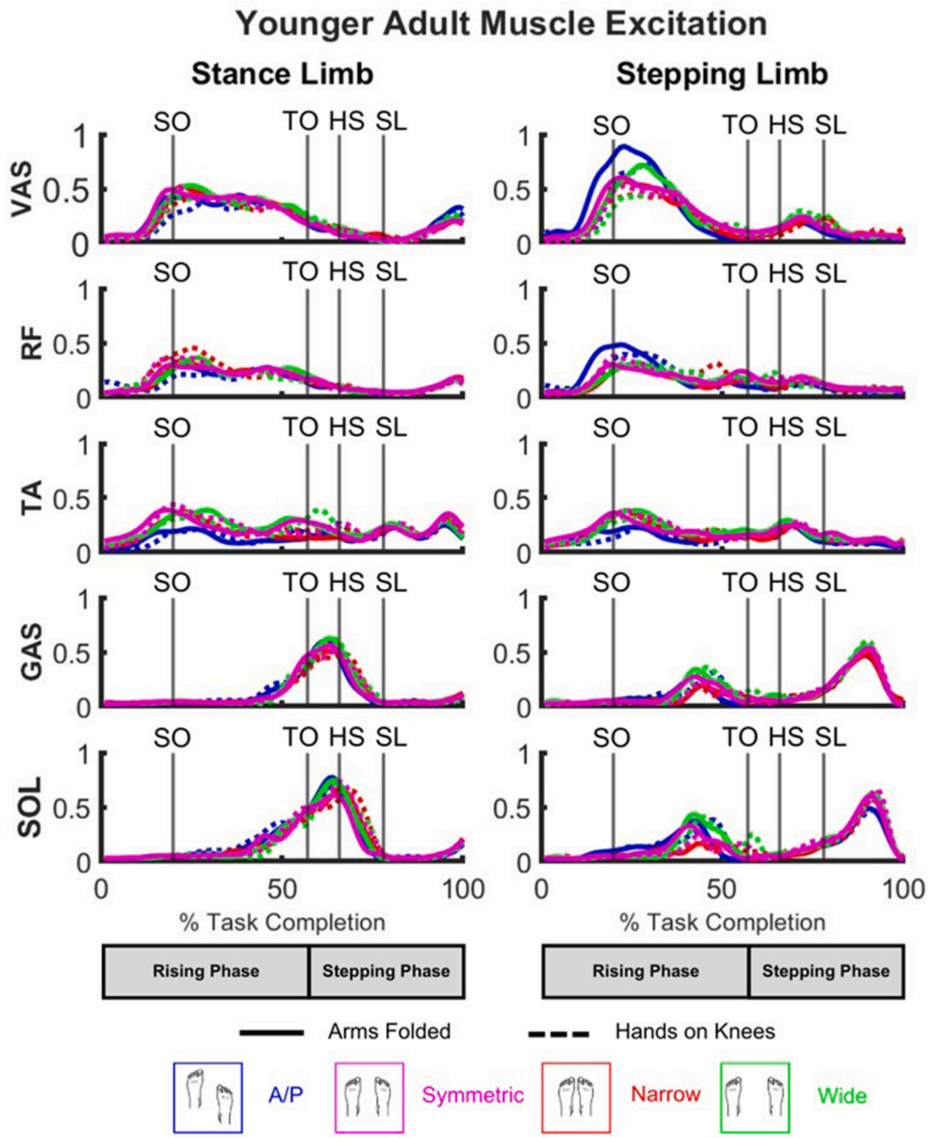

Fig. 5. Average normalized vastus lateralis (VAS), rectus femoris (RF), tibialis anterior (TA), gastrocnemius (GAS), and soleus (SOL) muscle excitation linear envelopes for younger adults in STW for four initial foot positions and two arm placements. Vertical lines indicate STW (0–100%) events seat off (SO), toe-off (TO), heel strike (HS), and stance limb toe-off (SL). See Fig. 2 for full definitions of each STW event. For a color version of the figure, please refer to the online version of the manuscript. Significant main, interaction, and pairwise post hoc differences are detailed in the text and numerical values are provided in Supplementary Tables S3-S7.

STW with aging.

Our hypothesis that rising from the A/P offset initial foot position would increase peak knee extensor muscle excitation and moments for the stepping limb was supported by greater stepping limb VAS excitation and peak knee extension moments. This result is consistent with prior work demonstrating greater knee extensor muscle excitation from an A/P offset position in STS (Jeon, et al., 2019). We did not observe an increase in peak stepping limb RF excitation in the A/P offset condition, which is likely because this biarticular muscle has different functional roles from VAS and provides less vertical support of the body COM to rise (Caruthers et al., 2016). In addition, stance limb VAS excitation when rising from the A/P offset foot position was lower, indicating asymmetric muscular demands. The A/P offset position may facilitate forward motion in STW, but it also requires greater muscle excitation and weight bearing on the offset limb, which may not be feasible for individuals with joint degeneration and pain. A significant age by foot interaction effect indicated that older adults required greater knee extension moments on their offset limb to rise than younger adults, suggesting that rising from an A/P offset foot position could be more challenging for older adults with mobility deficits.

Our hypothesis that arm-supported rising from the knees would require less knee extensor muscle excitation and a smaller peak knee extension moment was partially supported. Peak VAS excitation on the stepping limb was lower, but there was no difference in VAS excitation on the stance limb and no difference in RF on either limb. Peak knee extension moment was lower on the stepping limb and trended significantly less on the stance limb with arm support ($p=0.053$). The reduction in peak knee extension moment is consistent with prior STS studies of rising with arm support from armrests (Burdett, et al., 1985; Arborelius, et al., 1992; Seedhom and Terayama, 1976). Note, except for stepping limb VAS, we did not see smaller knee extensor peak excitation in conjunction with these lower knee extension moments with arm-supported rising. Similar muscle excitations combined with lower joint moments observed in this study may be explained by multiple factors, such as excitations from other knee muscles or functional roles of the knee extensors in these two conditions. There is also a distinction

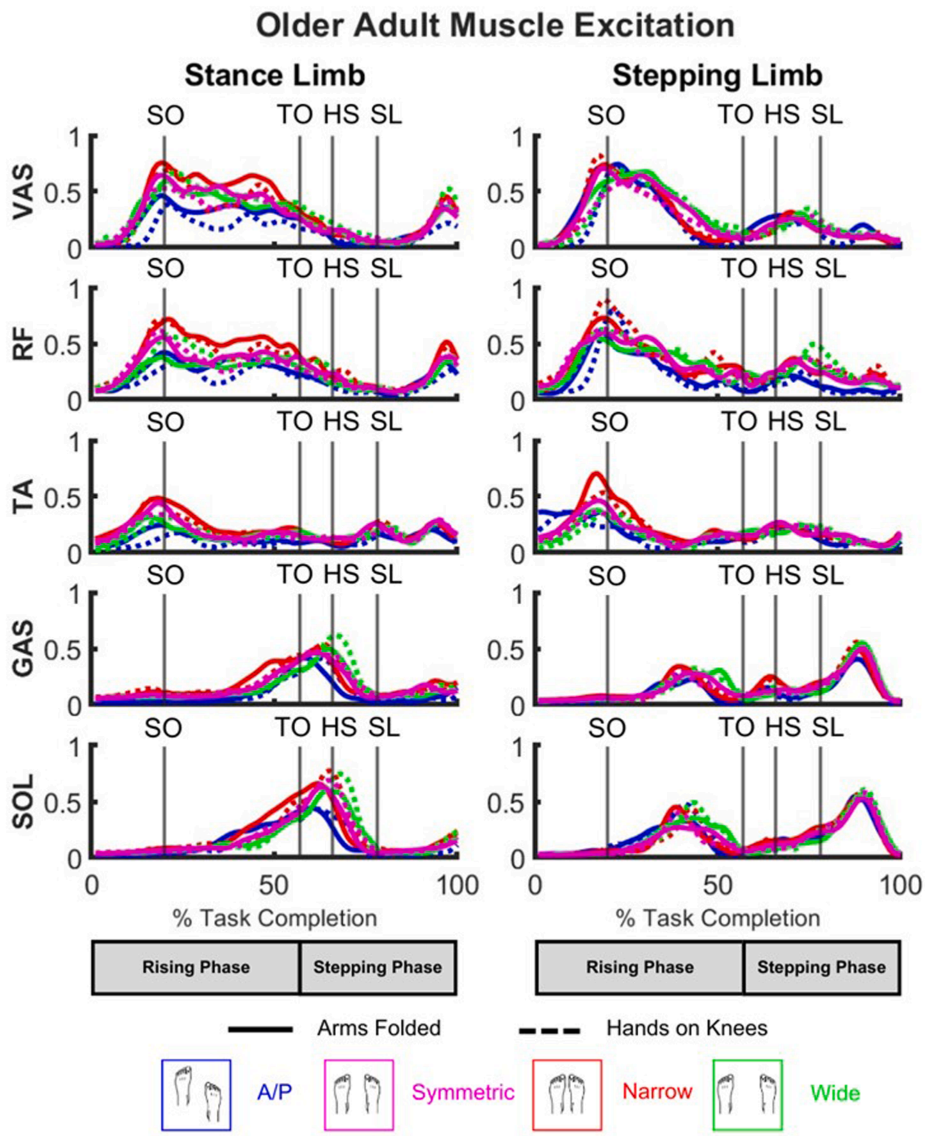

Fig. 6. Average normalized vastus lateralis (VAS), rectus femoris (RF), tibialis anterior (TA), gastrocnemius (GAS), and soleus (SOL) muscle excitation linear envelopes for older adults in STW from four initial foot positions and two arm placements. Vertical lines indicate STW (0–100%) events seat off (SO), toe-off (TO), heel strike (HS), and stance limb toe-off (SL). See Fig. 2 for full definitions of each STW event. For a color version of the figure, please refer to the online version of the manuscript. Significant main, interaction, and pairwise post hoc differences are detailed in the text and numerical values are provided in Supplementary Tables S3-S7.

between arm-supported rising from armrests in prior work and from the knees in this study. A significant arm by age interaction effect indicated that arm support reduced the required stance limb RF and stepping limb VAS excitation to rise in older adults but not younger adults, which may be driven by the higher baseline excitation of these muscle groups in older adults. Arm-supported rising may therefore facilitate STW transitions by reducing knee extensor muscle excitation in older adults, and the efficacy of this strategy likely varies with individual capability.

Older adults required greater stepping limb ankle muscle excitation in conjunction with smaller ankle plantarflexion moments to rise compared to younger adults, supporting our hypothesis. The TA has been previously shown to stabilize against posterior movement of the COM when walking (Afschrift, et al., 2019). Greater SOL and GAS excitation combined with greater TA excitation reflects altered muscle recruitment in older adults, consistent with greater co-contraction to maintain static (Warnica, et al., 2014) and dynamic postural control (Iwamoto, et al., 2017). A significant age by foot interaction suggests that the A/P offset and narrow foot positions could allow older adults to reduce TA excitation. Younger adults required less offset limb TA excitation to rise compared to older adults, who may require additional excitation to control balance.

Rising from the A/P offset foot position required greater peak GAS and SOL excitation and ankle plantarflexion moment on the stepping limb during rising compared to the stance limb, indicating the asymmetric demands when rising from the offset, stepping limb. Similar GAS and SOL excitation were required of both limbs to rise from the wide position as in the offset, stepping limb from the A/P offset position. In gait, the vertical and lateral acceleration of the body is modulated by the plantarflexors (John, et al., 2012; Pandy, et al., 2010). The lateral movement of the COM toward the stance limb when rising from a wide position is likely driven by greater stepping limb GAS and SOL excitation. Although a wider base of support can improve balance performance in some tasks (Kaminski and Simpkins, 2001; Yoo, et al., 2012), larger mediolateral GRFs and lateral movement are necessary to transition between rising from two limbs in a wide position into single limb stance. Therefore, rising from wide initial foot positions may be avoided to reduce plantarflexor demands to maintain lateral stability during STW, which may explain why older adults often choose to rise from a narrow position (van der Kruk et al., 2022).

A potential limitation in generalizing this work is variation in muscle strength across participants, which can affect muscle recruitment. In addition, our older participant group was healthy and had an average age of 62 years, which may not generalize to clinical adult populations in later decades. Our sample size, while able to detect multiple statistically significant differences, may not capture all biomechanical differences between older and younger adults. We normalized electromyography signals to functional tasks, which are dependent on effort. However, this limitation also applies to maximum voluntary contraction and STW tasks.

5. Conclusion

This study systematically compared lower limb joint moments and muscle excitation across initial foot positions and arm placements in younger and older adults during STW transitions. Older adults had greater knee extensor moments and excitation compared to younger adults during STW. Older adults also generated greater peak TA, GAS and SOL excitation alongside smaller ankle plantarflexion moments when rising, suggesting older adults may use altered muscle recruitment to maintain dynamic postural control. Rising from the A/P offset position required greater peak VAS excitation and greater knee extension and ankle plantarflexion moments on the stepping limb, while reducing the demand for knee extension and ankle plantarflexion on the stance limb. The wide position required greater peak GAS and SOL stepping limb excitation, highlighting greater plantarflexor demand to maintain lateral stability during the transition between rising from two limbs into single limb stance. Arm-supported rising from the knees lowered the VAS excitation and knee extension moment on the stepping limb but not in the stance limb. Initial arm placement and foot position affect the biomechanics of STW across the lifespan. These results can guide clinical evaluations and movement training of older adults of daily transitional tasks.

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CRediT authorship contribution statement

Michael F. Miller: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Eline van der Kruk:** Writing – review & editing, Supervision, Conceptualization. **Anne K. Silverman:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2024.112367.

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