Effects of Age and Attentional Focus on the Performance and Coordination of the Sit-to-Stand Task

Valéria Andrade[a*], PT, MSc, Alysson Mazoni[b], PhD, Camila Santos[c], PT, MSc, Daniela Mattos[d], PhD, Suvobrata Mitra[e], PhD, Juliana Ocarino[c], PhD, Daniela Vaz[c], PhD

[a]Center for Cognition, Action, & Perception, Department of Psychology, University of Cincinnati, Cincinnati, OH, USA; [b]InSySPo, System Innovation Institute of Geosciences, Universidade Estadual de Campinas, Campinas, SP, Brazil; [c]Department of Physical Therapy, School of Physical Education, Physical Therapy, and Occupational Therapy, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil; [d]Department of Neurology, Washington University School of Medicine in St. Louis, St. Louis, MO, USA; [e]Department of Psychology, Nottingham Trent University, Nottingham, UK

***Corresponding Author:** Valéria Andrade, Center for Cognition, Action, & Perception, Department of Psychology, Edwards Center 1, University of Cincinnati, Cincinnati, OH, 45221-0376 USA. Email: pintova@mail.uc.edu

ORCID
Valéria Andrade: https://orcid.org/0000-0003-3140-510X
Alysson Mazoni: http://orcid.org/0000-0001-5265-6894
Camila Santos: http://orcid.org/0000-0002-9131-9118
Daniela Mattos: http://orcid.org/0000-0003-3396-1951
Suvobrata Mitra: https://orcid.org/0000-0001-7620-4809
Juliana Ocarino: https://orcid.org/0000-0001-9404-1695
Daniela Vaz: https://orcid.org/0000-0003-0470-6361

Word Count: 5399

Abstract

This study investigated whether age and attentional focus affect synergy organization of sit-to-stand (STS), an essential movement for mobility and independence. Young and older adults performed 40 STS trials of STS while holding a cup under internal (IF) and external focus (EF) instructions. Uncontrolled manifold analysis was used to decompose trial-to-trial variability in joint kinematics into variability that preserves (V_{UCM}) and interferes with (V_{ORT}) four control variables: the horizontal and vertical positions of the center of mass (CoM) and the cup. V_{UCM} was significantly higher than V_{ORT} for all control variables in both age groups and focus conditions, indicating concurrent postural and supra-postural synergies. Compared with young adults, older adults demonstrated higher V_{UCM} for all control variables and higher V_{ORT} for all variables except the vertical position of the cup. IF instructions benefited older adults, leading to decreased Vort and thus decreased variability of the vertical position of CoM and the horizontal and vertical positions of the cup. Results suggest that older adults may use higher indices of motor flexibility than young adults to compensate for less accurate control of postural and supra-postural variables. For older adults, IF instructions may improve STS control at the postural and supra-postural levels.

Keywords: sit-to-stand, attentional focus, aging, uncontrolled manifold

Introduction

Declining performance in the sit-to-stand (STS) task (performed around 60 times per day) (Dall & Kerr, 2010) is a key indicator of reduced mobility in old age and greater risk of falls, hospitalization, and nursing home admission (Makizako et al., 2017; Buatois et al., 2008; Lord et al., 2002; Tinetti et al., 1988). There is, therefore, a significant interest in understanding how mobility tasks of daily living are controlled, how control changes with age, and how control may be improved with rehabilitative interventions.

Performance of STS requires coordination of multiple and redundant joint motions across the body to control the displacement of the whole-body center of mass (CoM) from a lower position with a larger base of support (buttocks and feet) to a higher position with a smaller and less stable base (feet). Adequate coordination should produce movements that are stable and flexible enough to produce controlled displacement of the CoM while accommodating changing contextual demands such as varying seat heights, age-related declining muscle strength, or the need to perform a concurrent manual task like keeping a cup of coffee stable during movement (Greve et al., 2019; Hsu, 2014; Hsu & Scholz, 2012). The central nervous system promotes movement stability and flexibility by organizing neuromuscular synergies (Latash & Huang, 2015; Latash, 2008; Latash et al., 2002, 2007; Scholz & Schöner, 1999). In the last two decades, the analysis of synergies has been greatly advanced via the uncontrolled manifold (UCM) approach (Latash, 2008; Latash et al., 2007; Reisman et al., 2002; Scholz & Schöner, 1999).

In STS, the rising trajectory of the CoM during STS can be generated through a variety of equivalent (redundant) combinations of joint motions. Over repeated STS attempts, joint motions show substantial variability (Scholz et al., 2001). UCM decomposes this variability into two sets: V_{UCM} and V_{ORT}. V_{UCM} is the set of all joint motion values compatible with a stable value of an important control variable, such as the position of the CoM during STS (Anan et al., 2017; Greve et al., 2013, 2019; Scholz et al., 2001; Scholz & Schöner, 1999). Variability within this set does not affect STS performance; all joint motions within the V_{UCM} set are redundant with respect to the CoM position, and they can be flexibly interchanged from trial to trial. Such variability is good in the sense that it maintains STS stability while affording flexibility (Scholz et al., 2001; Scholz & Schöner, 1999). Therefore, this set is "uncontrolled" (i.e., free to be exploited in order to perform the STS task). In contrast, some combinations of joint motions interfere with the position of the CoM and thus form another set, V_{ORT} (orthogonal to V_{UCM} in mathematical space), that negatively affects performance (Latash et al., 2007; Scholz & Schöner, 1999). This kind of variability should be kept low for adequate STS performance. The relative difference between V_{UCM} and V_{ORT} provides an index of the strength of neuromuscular synergies stabilizing functional movement (Latash et al., 2007).

Young and older adults may employ similar multi-joint synergies (V_{UCM} relative to V_{ORT}) to stabilize the CoM during STS (Greve et al., 2013, 2019) and to stabilize the end-point during a goal directed upper extremity reaching task (Greve et al., 2017), but research also suggests that there may be differences in neuromuscular synergies between the two groups (Rosenblatt et al., 2020; Olafsdottir et al., 2007, 2008; Shinohara et al., 2004). For example,= synergies of older adults that stabilize the CoM during balance recovery are less flexible than those of young adults (Hsu et al., 2013), and the synergy index in multi-digit pressing and prehensile tasks is also reduced compared with young adults (Olafsdottir et al., 2007, 2008; Shinohara et al., 2004). In contrast, older adults showed stronger multi-joint synergies stabilizing the swing limb during a cued walking task than young adults (Rosenblatt et al., 2020). Evidence shows that flexible synergistic control allows for multitasking and supra-postural tasks (Hsu, 2014; Hsu & Scholz, 2012). A possible consequence of reduced synergy strength is a decreased adaptability in accommodating a concurrent manual task during STS (e.g., holding a drink). If older adults show less flexible synergies, they may have to prioritize either postural or supra-postural control at the expense of the other.

In the case of reduced synergistic stabilization of movement, rehabilitative interventions should promote improvements in STS control. One possible way to modify movement control is through cognitive strategies to focus attention (Fietzer et al., 2018; Lohse et al., 2014). For a range of skills (e.g., balancing, jumping, throwing), focusing attention on the effects of movement on objects or the environment—external focus (EF)—yields better movement efficiency (i.e., more fluent, economical, and automatic movements) and effectiveness (i.e., more accurate, consistent, and reliable movements) than attending to some aspect of body movement itself—internal focus (IF) (Wulf, 2013). The benefits of EF affect performance hypothetically through changes in underlying coordination: the "constrained action hypothesis" suggests that IF induces a conscious type of control, interfering with automatic coordination processes (Lohse et al., 2014; Wulf, 2013), whereas EF can improve coordinative flexibility (Fietzer et al., 2018) by prioritizing goal-relevant information for fluid movement coordination (de Melker Worms et al., 2017a; Young & Williams, 2014). In dart throwing, for example, EF increases trial-to-trial variability of joint motions while improving the accuracy and consistency of dart strike location (Lohse et al., 2010). Thus, in UCM terms, an EF could increase covariation of joint motions (increase in V_{UCM}) and increase performance accuracy (decrease in $\mathrm{V}_{\mathrm{ORT}}$). The benefits of EF may also be more pronounced in older adults if EF instructions reduce their greater tendency to focus internally on challenging tasks (Mak et al., 2021; Chu & Wong, 2019; Young et al., 2016). Holding a cup stable makes for a useful experimental model to test these expectations because it creates a natural supra-postural task goal that serves as an external referent to which attention may or may not be directed during STS, depending on instructions. Previous studies have shown that an EF on a supra-postural task goal increases the accuracy and consistency of postural control (Wulf et al., 2003, 2004; McNevin & Wulf, 2002).

This study investigated synergistic coordination in young and older adults during STS while they held a cup under EF and IF conditions. Our first goal was to investigate whether age affects synergy organization of STS at the postural and supra-postural levels. In UCM terms, differences between young and older adults would be seen in V_{UCM} and V_{ORT} for the CoM and cup positions; but, based on the literature, we cannot predict a direction of this difference. Our second goal was to determine the effects of EF and IF for young and older adults. Here, we were interested in the effect of EF (focus on the cup) or IF (focus on the hand) on CoM and cup control during STS. We expected EF to yield more flexible (greater V_{UCM}) and more accurate (lower V_{ORT}) CoM and cup control for both age groups, based on the "constrained action hypothesis" and previous preliminary findings (Fietzer et al., 2018; Lohse et al., 2010). For older adults, we expected a greater difference in favor of EF (thus an interaction effect between age and focus) because we expected EF instruction to counteract their tendency to pay deliberate attention to their movements (i.e., using IF) when performing challenging tasks (Mak et al., 2021; Chu & Wong, 2019; Young et al., 2016).

Methods

Participants

A convenience sample of 20 healthy older adults (6 males and 14 females; 69.80 ± 4.57 years; 25.43 ± 3.65 kg/m^2) and 26 healthy young adults (6 males and 20 females; 23.00 ± 2.87 years; 22.40 ± 2.67 kg/m^2) participated in the study. Inclusion criteria were: (1) be 65 years or older or between 18 and 35 years; (2) be right-handed; (3) have normal or corrected-to-normal vision; (4) have no musculoskeletal or neurological symptoms affecting STS; and (5) have no cognitive disorders affecting the ability to understand and follow instructions. Participants would be excluded if they complained of joint pain or could not complete the number of trials required for the task. The study protocol followed the Declaration of Helsinki and was approved by the local institutional review board. Written informed consent was obtained from all participants.

Equipment and set-up

Participants performed STS while holding a cup under EF and IF attention conditions. This study focused on the sagittal plane analysis because motion was largely restricted to that plane (Scholz & Schöner, 1999). We collected the experimental data with four capture units of the Codamotion System (Charnwood Dynamics, Rothley, UK) at a sampling rate of 100 Hz (Greve et al., 2013). Marker placement is illustrated in Figure 1. Four-marker rigid clusters were attached to the left shank, thigh, forearm, and arm. Three markers were placed on the cup and three on the participants' left hand (on the heads of the second and fifth metacarpals and the middle of the third metacarpal). Markers were also placed on the left temple, left mastoid process, and spinous processes of the seventh cervical, the twelfth thoracic, and the fifth lumbar vertebrae. The following landmarks were obtained with a virtual point marker: lateral malleoli, lateral epicondyles of the femur, anterior superior iliac spine, great trochanter, acromion, lateral epicondyle of the humerus, and the styloid process of the ulnae. The markers were used to define virtual segments corresponding to the shank, thigh, pelvis, lower trunk, upper trunk, neck, head, arm, forearm, hand, cup, and the intervening joints.

[Figure 1 near here]

Experimental procedure

Participants sat on a stool (the height of which was set at 80% of their shank length) holding a cup with their non-dominant hand and resting it on their thigh. The non-dominant hand and a low seat height were chosen because attentional focus effects are more pronounced in more challenging tasks (Landers et al., 2005). In the first trial, participants freely chose the most comfortable initial positions of the buttocks, thighs, feet, and cup. These positions were marked with tape and reproduced in all subsequent trials.

Participants performed 45 repetitions of the task at a self-selected comfortable speed while looking at an eye-level target placed on the wall at a distance of 1.3 m (McNevin et al., 2003). By observing participants' gaze, the experimenter ensured that they were looking at the target on every trial. Participants were free to reposition their right hand but were not allowed to push with their hand on the thighs or swing the right arm.

Each trial began with a verbal "go" signal. The first five trials had no specific instructions of focus of attention. Participants then performed two blocks of 20 trials each, one for the EF condition and one for the IF condition. Blocks were separated by a 10-minute interval. The order of the blocks (EF-IF or IF-EF) was counterbalanced for each participant to avoid order effects. Instructions were designed to be relevant for real-life situations when one has to stand up with a cup while avoiding liquid spillage. EF instructions were to *"focus attention on keeping the cup stable"* (inducing a focus outside the body, on the cup) whereas IF instructions were to *"focus attention on keeping the hand stable"* (inducing a focus internal to the body, on the hand) (Zarghami et al., 2012; Castaneda & Gray, 2007; Parr & Button, 2009). The experimenter reminded participants of the focus instructions after every two trials. After every 10 trials, participants took a 2-minute break, and the experimenter asked them *"How well were you able to follow the instructions in the last 10 repetitions?"* on a graded scale of 1 (poorly) to 10 (excellently). None of the participants reported fatigue or pain. The data collection session lasted approximately 45 minutes, including preparation.

Data reduction

Marker position data were exported to MATLAB (R2017a, Mathworks, Natick, MA). Marker position time series were filtered with a 6-Hz low-pass filter (4th order Butterworth). Cubic spline interpolation was used to estimate marker positions if data were lost for less than 10 consecutive frames. Trials with data gaps greater than 10 frames were discarded. Marker position was used to calculate segment lengths and joint angles in the sagittal plane (Scholz and Schöner 1999). Joint angles from all trials were visually examined for consistency across repetitions, and deviant trials were discarded before further analysis. On average, there were 36.54 (± 2.17) and 38.50 (± 1.70) good trials per older and young adult, respectively.

The total body center of mass (CoM) position was calculated from position data and anthropometric estimates (Winter, 2009). STS onset and termination were determined automatically and checked visually for all trials. Onset was defined at the point that the CoM horizontal velocity exceeded 5% of its baseline value, before its largest upward deviation. Movement termination corresponded to the last downward deviation of the COM vertical velocity when it crossed the value corresponding to 5% of its baseline. For each trial, the portion from movement onset to termination was normalized to 200 samples in evenly spaced steps with the cubic spline interpolation. STS phases were defined according to Greve et al. (2013) within percentages of the time-normalized trials: preparatory phase (1–30%), lift-off (31–60%), and extension phase (61–100%).

STS performance

Total movement time was used as a performance indicator for each STS trial. Shorter movement times indicated better performance than longer movement times. Slower movements were expected in older adults (Greve et al., 2013).

STS synergies: UCM analysis

STS UCM measures were V_{UCM} and V_{ORT} for the horizontal and vertical positions of the CoM and cup. UCM analysis involved three steps (Latash & Zatsiorsky, 2016; Latash et al., 2007), which are detailed in Appendix 1. First, the relevant joint angles and the control variables expected to be stabilized by covariation of the joint angles were defined (in the sagittal plane). Second, geometric models (Figure 2 and Appendix 1) linking joint angle changes to control variable changes were defined. Third, projections of variance in the space of elemental variables onto the UCM (V_{UCM}) and its orthogonal complement (V_{ORT}) were calculated. V_{UCM} and V_{ORT} were calculated at every time frame of STS. The integral of each measure was computed for each of the STS phases (preparatory phase [1%–30%]; liftoff [31%–60%] and extension [61%–100%]). Based on Greve et al. (2013), the analysis focused on the two last phases.

[Figure 2 near here]

Statistical analyses

Statistical analyses were performed using custom RStudio (RStudio, Inc., Boston, MA) scripts. All UCM measures were log-transformed to meet analysis assumptions. For movement time measure, mixed-effects modeling was implemented with age, focus, and their interactions as fixed effects and participant as random effect. Prior to STS coordination analysis, we conducted a preliminary analysis to ensure that $\mathrm{V}_{\mathrm{UCM}}$ was significantly higher than $\mathrm{V}_{\mathrm{ORT}}$. For the preliminary analysis, mixed-effects modeling was implemented with age, type of variance ($\mathrm{V}_{\mathrm{UCM}}$ or $\mathrm{V}_{\mathrm{ORT}}$), phase, and their interactions as fixed effects and participant as random effect. For

UCM measures, mixed-effects modeling was implemented with age, focus, phase, and their interactions as fixed effects and participant as random effect. A backward stepwise approach was used for model building, as described in West et al. (2015). Models were trimmed by removing nonsignificant effects individually, progressing from higher- to lower-order interactions. The final model only included higher-order interactions that significantly improved model fit and all component lower-order interactions and main effects. Simple-effect analysis and pairwise comparisons were performed to follow up on significant interactions. Degrees of freedom for pairwise comparisons were corrected using the Kenward-Roger method. Alpha was adjusted with the Tukey correction. Level of significance was set at $p < .05$.

Results

Manipulation check

The average grade answer to the question *"How well were you able to follow the instructions in the last 10 repetitions?"* for the older adults under EF and IF instructions were 9.8 ± 0.4 and 9.5 ± 0.7, respectively. For young adults, the average grade answers were 8.4 ± 1.4 and 8.1 ± 1.6, respectively. Although grades of older adults were significantly higher than young adults ($F[1;45] = 19.97$, $p = 0.001$, $partial\ \eta^2 = 0.31$), both age groups followed instructions very well to excellently.

Total movement time

The final model for total movement time revealed no significant main effects or interactions, all ps > .05. Overall, participants took on average 3.13 ± 0.23 seconds to complete each STS repetition.

STS coordination

Preliminary analysis

The final models for horizontal and vertical CoM position, and horizontal cup position showed significant age x type of variance and type of variance x phase interactions, all *p*s < .001. The final model for vertical cup position showed significant age x type of variance interaction, $p < .01$. As expected, follow-up pairwise comparisons revealed that V_{UCM} was significantly higher than V_{ORT} regardless of age and movement phase for all the four coordination variables analyzed, all *p*s < .01 (Figure 3).

[Figure 3 near here]

V_{UCM} and V_{ORT} for horizontal CoM position

The final model for V_{UCM} for horizontal CoM position showed significant main effects of age, $t(45.50) = - 2.64$, $p = .01$, and phase, $t(131.80) = - 6.79$, $p < .001$. V_{UCM} was significantly higher for older ($M = 0.0065$, $SD = 0.0037$) than young participants ($M = 0.0046$, $SD = 0.0020$) (Figure 4a), and for phase 2 ($M = 0.0063$, $SD = 0.0031$) than phase 3 ($M = 0.0046$, $SD = 0.0027$). The general patterns of variation of V_{UCM} for horizontal CoM position are shown in Figure 3a.

The final model for V_{ORT} for horizontal CoM position showed significant main effect of age, $t(44.20) = -5.07$, $p < .001$ (Figure 4b), and significant focus x phase interaction, $t(124.87) = 2.11$, $p = .04$. Follow-up pairwise comparisons revealed that, although movement phase interfered in the direction of V_{ORT} difference, there were no significant differences between focus of attention conditions, all *p*s > .05 (Figure 5a). V_{ORT} was significantly higher for older ($M = 0.0004$, $SD = 0.0003$) than for young participants ($M = 0.0002$, $SD = 0.0001$) (Figure 4b). The general patterns of variation of V_{ORT} for horizontal CoM position is shown in Figure 3a.

[Figure 4 near here]

[Figure 5 near here]

V_{UCM} and V_{ORT} for vertical CoM position

The final model for V_{UCM} for vertical CoM position showed significant main effects of age, *t*(45.49) = -2.61, *p* = .01, and phase, *t*(131.79) = -7.20, *p* < .001. V_{UCM} was significantly higher for older (*M* = 0.0064, *SD* = 0.0037) than young participants (*M* = 0.0045, *SD* = 0.0019) (Figure 4a), and for phase 2 (*M* = 0.0062, *SD* = 0.0031) than phase 3 (*M* = 0.0045, *SD* = 0.0026). The general patterns of variation of V_{UCM} for vertical CoM position are shown in Figure 3b.

The final model for V_{ORT} for vertical CoM position showed significant age x focus, *t*(131.75) = 3.67, *p* < .001, and focus x phase interactions, *t*(129.99) = 2.05, *p* = .04. Follow-up pairwise comparisons revealed that V_{ORT} was significantly higher when older participants were in the EF condition (*M* = 0.0023, *SD* = 0.0016) than in the IF condition (*M* = 0.0016, *SD* = 0.0015), *p* < .0001 (Figure 5b). This difference between focus was not observed for young participants, (EF: *M* = 0.0010, *SD* = 0.0007; IF: *M* = 0.0011, *SD* = 0.0007), *p* > .05 (Figure 5b). Additionally, V_{ORT} for EF were significantly higher than for IF regardless of age, but only at phase 2 (Phase 2: EF: *M* = 0.0016, *SD* = 0.0016, IF: *M* = 0.0011, *SD* = 0.0008; Phase 3: EF: *M* = 0.0015, *SD* = 0.0010, IF: *M* = 0.0016, *SD* = 0.0014). The general pattern of variation of V_{ORT} for vertical CoM position is shown in Figure 3b.

[Figure 5 near here]

V_{UCM} and V_{ORT} for horizontal cup position

The final model for V_{UCM} for horizontal cup position showed significant main effects of age, *t*(44.41)= -2.45, *p* = .02, and phase, *t*(127.82) = -6.05, *p* < .001. V_{UCM} was significantly higher for older (*M* = 0.0077, *SD* = 0.0042) than for young participants (*M* = 0.0055, *SD* =

0.0025) (Figure 4a), and for phase 2 (*M* = 0.0074, *SD* = 0.0036) than for phase 3 (*M* = 0.0055, *SD* = 0.0031). The general pattern of variation of V_{UCM} for horizontal cup position is shown in Figure 3c.

The final model for V_{ORT} for horizontal cup position showed significant age x focus x phase interaction, *t*(129.99) = -2.13, *p* = .03. To follow-up on the age x focus x phase interaction, the model was fit separately for each movement phase. Results showed significant age x focus interaction, but only for phase 2, *t*(42.95) = 2.19, *p* = .03. For phase 2, we found a difference between EF and IF, but only for older participants. V_{ORT} was significantly higher for older participants in the EF condition (*M* = 0.0021, *SD* = 0.0012) than in the IF condition (*M* = 0.0014, *SD* = 0.0010) (Figure 5c). For phase 3, there was no significant interaction. However, V_{ORT} was significantly higher for older (*M* = 0.0006, *SD* = 0.0003) than for young participants (*M* = 0.0003, *SD* = 0.0002), *t*(78.06) = -3.09, *p* < .01 (Figure 5c). The general pattern of variation of V_{ORT} for horizontal cup position is shown in Figure 3c.

V_{UCM} and V_{ORT} for vertical cup position

The final model for V_{UCM} for vertical cup position showed significant main effect of age, *t*(61.92) = -2.95, *p* < .01, and phase, *t*(130.73) = - 6.48, *p* < .001. V_{UCM} was significantly higher for older (*M* = 0.0078, *SD* = 0.0043) than for young participants (*M* = 0.0057, *SD* = 0.0027) (Figure 4a), and for phase 2 (*M* = 0.0075, *SD* = 0.0037) than for phase 3 (*M* = 0.0056, *SD* = 0.0032). The general pattern of variation of V_{UCM} for vertical cup position is shown in Figure 3d.

The final model for V_{ORT} for vertical cup position showed significant main effect of phase, *t*(128.05) = -4.60, *p* < .001. V_{ORT} was significantly higher for phase 2 (*M* = 0.0005, *SD* = 0.0003) than phase 3 (*M* = 0.0004, *SD* = 0.0002). There was also a significant age x focus interaction, *t*(128.03) = 3.25, *p* < .01. Follow-up comparisons revealed a difference between EF and IF, but only for older participants. V_{ORT} was significantly higher when older participants were in the EF condition (*M* = 0.0005, *SD* = 0.0003) than when they were in the IF condition (*M* = 0.0004, *SD* = 0.0003) (Figure 5d). The general pattern of variation of V_{ORT} for vertical cup position is shown in F

Discussion

This study employed UCM analysis to investigate synergistic organization of joint angles in the STS of young and older adults while holding a cup and receiving IF or EF instructions. We found evidence for concurrent neuromuscular synergies (Latash et al., 2007) stabilizing both the CoM position, at the postural level, and the cup position, at the supra-postural level. V_{UCM} was consistently higher than V_{ORT} in all movement phases, age groups, and focus conditions for all four control variables analyzed (horizontal and vertical CoM and cup positions, Figure 3). Concerning our first goal, we found evidence that age does affect synergy organization of STS at the postural and supra-postural levels (Figure 4). The possible reduction in synergy flexibility (i.e., lower V_{UCM} values) for older adults compared to young adults was not confirmed by our results. In general, both V_{UCM} and V_{ORT} values were higher for older than for young adults. Concerning our second goal, we found evidence that the focus of attention affects older people differently than young people; however, the evidence did not confirm our expectation that EF would lead to higher V_{UCM} and lower V_{ORT} values than IF (Figure 5).

Before discussing age and focus-related differences in synergistic organization, we note that V_{UCM} for the vertical and horizontal as well as V_{ORT} for the horizontal CoM position were significantly higher during lift-off than during the extension phase of STS. This finding is consistent with previous evidence of significantly higher V_{UCM} and V_{ORT} for control of ground reaction forces (GRF) during the lift-off compared with the extension phase (Greve et al., 2013). Lift-off is a critical phase for body coordination during STS because trunk momentum needs to be transferred into posterior-anterior and vertical movements of the CoM. In this phase, several kinematic adaptations used by older adults such as larger trunk flexion, decreased peak GRF, and lower propulsive power imparted to the CoM become evident (Yamada & Demura, 2010; Alexander et al., 2001; Gross et al., 1998; Hughes et al., 1994, 1996). Beyond such biomechanical adjustments, older adults may also rely on adaptations of interjoint coordination during STS task, changing co-variation among lower and upper extremity joints, trunk, and neck to seek stability (Greve et al., 2013) and preserve performance. Accordingly, our results show that age and focus effects on interjoint coordination measures (V_{UCM} and V_{ORT}) were particularly evident during the lift-off phase, while performance measured as total movement time was preserved in older adults (no significant difference between groups).

Our results indicate that, compared with young adults, older adults increase V_{UCM} values for all four control variables (Figure 4a). These results suggest that older adults employ greater motor flexibility, exploring a greater number of equivalent motor solutions leading to the same motor output during STS (Greve et al., 2013). Such increased flexibility is usually interpreted as providing enhanced capacity to perform concurrent tasks, handle new constraints or react to perturbations (Greve et al., 2013; Hsu & Scholz, 2012; Klous et al., 2010; Zhang et al., 2008). However, in older adults, it may not indicate greater potential to better performance, but rather a necessary compensation to deal with age-related functional decline that includes decreases in muscle strength and power (Thompson, 2009; Faulkner et al., 2007), integration of proprioceptive feedback (Goble et al., 2009), coordination of agonist-antagonist muscle pairs (Hortobágyi & Devita, 2006) and cognitive functions involved in postural control (Morris et al., 2016; Seidler et al., 2010; Woollacott & Shumway-Cook, 2002). In this sense, increased V_{UCM} may indicate greater use of compensatory mechanisms (Greve et al., 2013). There is preliminary evidence to support this interpretation. Greve et al. (2013) showed that older adults who have low knee extensor muscle strength increased co-variation among the available joint motions to keep GRF stable, although a later study observed that V_{UCM} for CoM position remained unaffected by experimentally increased force or balance demands (Greve et al., 2019).

Our V_{ORT} results may also support this interpretation. Unlike previous STS studies (Greve et al., 2013, 2019), we also found increases in V_{ORT} values for all control variables, except the vertical cup position (Figure 4b). Thus, in our task with concurrent postural and supra-postural demands, older adults showed more flexible, but more importantly, less accurate joint motion patterns than young adults. Evidence indicates that older adults perform the STS at a much higher percentage of their maximal effort (Greve et al., 2013; Hortobágyi et al., 2003; Alexander et al., 1991, 2001; Gross et al., 1998; Hughes et al., 1996). With increased physical demand, larger sensorimotor noise in the system may cause increased V_{ORT} (Greve et al., 2015). The increase in V_{ORT} (less accurate performance) may be accompanied by a compensatory increase in V_{UCM} as a strategy to preserve stability (preserve the relation between V_{UCM} and V_{ORT}) (Eckardt & Rosenblatt, 2018; Greve et al., 2013, 2015, 2017). Previous studies on the stabilization of the mediolateral trajectory of the swing limb during gait (Eckardt & Rosenblatt, 2018), center of pressure displacement in quiet standing (Freitas & Duarte, 2012), and CoM during balance recovery (Hsu et al., 2013) also report increased V_{ORT} for older compared with young adults.

Next, we consider the observed effects of attentional focus on performance and synergistic coordination measures. Contrary to our expectations, the EF showed no beneficial increase in V_{UCM} or reduction in V_{ORT}. Surprisingly, the IF instruction benefited older adults during the lift-off phase, leading to decreased V_{ORT} and thus decreased variability of the vertical CoM position and the horizontal and vertical cup positions. In contrast, young adults were not affected by focus instructions (Figure 5). The observed IF advantage in older adults' postural and supra-postural control runs counter to the well-documented advantages of EF and disadvantages of IF for motor performance (McNevin et al., 2003; Wulf, 2013; Wulf et al., 2004). This unexpected result cannot be explained by low adherence to instructions because both young and older adults reported following instructions very well or excellently but may be related to the nature of the STS. We speculate that general postural and mobility skills that are acquired spontaneously during normal motor development with little declarative instruction (phylogenetic skills such as the STS) are less vulnerable to the usual negative interferences of an IF (de Melker Worms et al., 2017a; Young & Williams, 2015).

Evidence supports this speculation. One previous study failed to find any detrimental effects of IF or beneficial effects of EF on the performance of the STS while holding a cup at the level of movement outcomes: STS duration and cup angle, stability, and smoothness (Pinto et al., 2020). It is possible that IF has negative effects only for specialized, complex movement skills usually acquired with great amounts of explicit instruction in early practice. For these tasks, IF may revert the individual to an earlier declarative stage of learning and interfere with the automaticity of control, while EF might prioritize relevant, goal-related information for fluent coordination (de Melker Worms et al., 2017a; Young & Williams, 2014). Also, despite some previous research showing benefits of EF for posture and mobility skills (Richer, et al., 2017; Chiviacowsky et al., 2010; McNevin et al., 2013;), our results are consistent with more recent studies that report null effects for focus instructions for day-to-day posture and mobility skills

(Monahan & Hurley, 2021; Mak et al., 2020; Chow et al., 2019; de Melker Worms et al., 2017a, 2017b; Richer et al., 2017; Yogev-Seligmann et al., 2017; Landers et al., 2016; De Bruin et al., 2009).

Possible reasons for the beneficial effects of the IF for older adults are unclear. An optimal individual attentional strategy may depend on motor imagery ability and personal preferences (Sakurada et al., 2016, 2017; Maurer & Munzert, 2013). Focusing internally may have been a more familiar, less attention-demanding strategy for older adults. Our observation that an IF may benefit postural and supra-postural control for older adults is a novel finding that merits further investigation, especially with respect to the possibility of improving the postural performance through dual-task practice wherein IF is applied to the control of supra-postural motor task.

Study limitations might have influenced the results. The use of an empty cup may not have made the task challenging enough for a beneficial effect of EF to emerge (Landers et al., 2005). Also, although participants reported following instructions very well to excellently, they were not asked about their actual attentional content. Different results at the level of the synergistic control of STS might have been found, had these variables been manipulated or controlled for. However, a recent study that increased STS difficulty by using a full cup with added speed demands and controlled for attentional content failed to reveal any beneficial effects of an EF at the level of performance. Interestingly, an IF was associated with better cup accuracy (lower variability of the inclination angle) during stand-to-sit, both for young and older adults (Pinto et al., 2020). It is also worth mentioning that joint angle measurement is a challenge for the field of motor control. The computation of joint angle variance within and orthogonal to the UCM assumes that the human body can be adequately represented as a set of rigid body elements connected by joints. Methodological studies investigating the precision of joint angle estimates based on this assumption would be valuable.

Conclusions

This study found evidence for control of the STS with concurrent neuromuscular synergies stabilizing both the CoM at the postural level, and the cup position at the supra-postural level. Our findings and previous studies on age differences in motor flexibility during STS and other tasks provide evidence that there is not a general decline in motor flexibility with aging. Rather, older adults may use higher indices of motor flexibility than young adults to compensate for less accurate control of postural and supra-postural variables. Contrary to expectations, for older adults, STS control may be improved both at the postural and supra-postural levels by IF rather than EF instructions.

Funding

This study was funded in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior-Brasil (CAPES)–001, Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP 2021/05823-1)), and a Newton Advanced Fellowship (140050) supported by the British Academy.

Disclosure of interest

The authors report there are no competing interests to declare.

Data availability statement

The data that support the findings of this study are available from the corresponding author, VA, upon reasonable request.

References

Alexander, N. B., Gross, M. M., Medell, J. L., & Hofmeyer, M. R. (2001). Effects of functional ability and training on chair-rise biomechanics in older adults. *Journals of Gerontology - Series A Biological Sciences and Medical Sciences*, *56*(9), M538–M547. https://doi.org/10.1093/gerona/56.9.M538

Alexander, N. B., Schultz, A. B., & Warwich, D. N. (1991). Rising from a chair: Effects of age functional ability on performance biomechanics. *Journals of Gerontology*, *46*(3), 91–98. https://doi.org/10.1093/geronj/46.3.m91

Anan, M., Hattori, H., Tanimoto, K., Wakimoto, Y., Ibara, T., Kito, N., & Shinkoda, K. (2017). The coordination of joint movements during sit-to-stand motion in old adults: the uncontrolled manifold analysis. *Physical Therapy Research*, *20*(2), 44–50. https://doi.org/10.1298/ptr.E9923

Buatois, S., Miljkovic, D., Manckoundia, P., Gueguen, R., Miget, P., Vançon, G., Perrin, P., & Benetos, A. (2008). Five times sit to stand test is a predictor of recurrent falls in healthy community-living subjects aged 65 and older. *Journal of the American Geriatrics Society*, *56*(8), 1575–1577. https://doi.org/10.1111/j.1532-5415.2008.01777.x

Castaneda, B., & Gray, R. (2007). Effects of focus of attention on baseball batting performance in players of differing skill levels. *Journal of Sport and Exercise Psychology*, *29*(1), 60–77. https://doi.org/10.1123/JSEP.29.1.60

Chiviacowsky, S., Wulf, G., & Wally, R. (2010). An external focus of attention enhances balance learning in older adults. *Gait and Posture*, *32*(4), 572–575. https://doi.org/10.1016/j.gaitpost.2010.08.004

Chow, V. W. K., Ellmers, T. J., Young, W. R., Mak, T. C. T., & Wong, T. W. L. (2019). Revisiting the relationship between internal focus and balance control in young and older adults. *Frontiers in Neurology*, *9*, 1131. https://doi.org/10.3389/fneur.2018.01131

Chu, C. K. H., & Wong, T. W. L. (2019). Conscious Postural Control During Standing on Compliant Surface by Older Adults. *Journal of Motor Behavior*, *51*(3), 342–350. https://doi.org/10.1080/00222895.2018.1481820

Dall, P. M., & Kerr, A. (2010). Frequency of the sit to stand task: An observational study of free-living adults. *Applied Ergonomics*, 41(1), 58-61. https://doi.org/10.1016/j.apergo.2009.04.005

De Bruin, E. D., Swanenburg, J., Betschon, E., & Murer, K. (2009). A randomised controlled trial investigating motor skill training as a function of attentional focus in old age. *BMC Geriatrics*, *9*, 15. https://doi.org/10.1186/1471-2318-9-15

de Melker Worms, J. L. A., Stins, J. F., van Wegen, E. E. H., Verschueren, S. M. P., Beek, P. J., & Loram, I. D. (2017a). Effects of attentional focus on walking stability in elderly. *Gait and Posture*, *55*, 94–99. https://doi.org/10.1016/j.gaitpost.2017.03.031

de Melker Worms, J. L. A., Stins, J. F., van Wegen, E. E. H., Loram, I. D., & Beek, P. J. (2017b). Influence of focus of attention, reinvestment and fall history on elderly gait stability. *Physiological Reports*, *5*(1), e13061. https://doi.org/10.14814/phy2.13061

Eckardt, N., & Rosenblatt, N. J. (2018). Healthy aging does not impair lower extremity motor flexibility while walking across an uneven surface. *Human Movement Science*, *62*, 67–80. https://doi.org/10.1016/j.humov.2018.09.008

Faulkner, J. A., Larkin, L. M., Claflin, D. R., & Brooks, S. V. (2007). Age-related changes in the structure and function of skeletal muscles. *Clinical and Experimental Pharmacology and Physiology*, *34*(11), 1091–1096. https://doi.org/10.1111/j.1440-1681.2007.04752.x

Fietzer, A. L., Winstein, C. J., & Kulig, K. (2018). Changing one's focus of attention alters the structure of movement variability. *Human Movement Science*, *62*, 14–24. https://doi.org/10.1016/J.HUMOV.2018.09.004

Freitas, S. M. S. F., & Duarte, M. (2012). Joint coordination in young and older adults during quiet stance: Effect of visual feedback of the center of pressure. *Gait and Posture*, *35*(1), 83–87. https://doi.org/10.1016/j.gaitpost.2011.08.011

Goble, D. J., Coxon, J. P., Wenderoth, N., Van Impe, A., & Swinnen, S. P. (2009). Proprioceptive sensibility in the elderly: Degeneration, functional consequences and plastic-adaptive processes. *Neuroscience and Biobehavioral Reviews*, *33*(3), 271–278. https://doi.org/10.1016/j.neubiorev.2008.08.012

Greve, C., Hortobágyi, T., & Bongers, R. M. (2017). Old adults preserve motor flexibility during rapid reaching. *European Journal of Applied Physiology*, *117*(5), 955–967. https://doi.org/10.1007/S00421-017-3584-2

Greve, C., Hortobágyi, T., & Bongers, R. M. (2019). Flexibility in joint coordination remains unaffected by force and balance demands in young and old adults during simple sit-to-stand tasks. *European Journal of Applied Physiology*, *119*(2), 419–428. https://doi.org/10.1007/s00421-018-4035-4

Greve, C., Hortobàgyi, T., & Bongers, R. M. (2015). Physical demand but not dexterity is associated with motor flexibility during rapid reaching in healthy young adults. *PLoS ONE*, *10*(5), e0127017. https://doi.org/10.1371/journal.pone.0127017

Greve, C., Zijlstra, W., Hortobágyi, T., & Bongers, R. M. (2013). Not all is lost: old adults retain flexibility in motor behaviour during sit-to-stand. *PloS One*, *8*(10), e77760. https://doi.org/10.1371/journal.pone.0077760

Gross, M. M., Stevenson, P. J., Charette, S. L., Pyka, G., & Marcus, R. (1998). Effect of muscle strength and movement speed on the biomechanics of rising from a chair in healthy elderly and young women. *Gait and Posture*, *8*(3), 175–185. https://doi.org/10.1016/S0966-6362(98)00033-2

Hortobágyi, T., & Devita, P. (2006). Mechanisms Responsible for the Age-Associated Increase in Coactivation of Antagonist Muscles. *Exercise and Sport Sciences Reviews*, *34*(1), 29–35. https://doi.org/10.1097/00003677-200601000-00007

Hortobágyi, T., Mizelle, C., Beam, S., & DeVita, P. (2003). Old adults perform activities of daily living near their maximal capabilities. *Journals of Gerontology - Series A Biological Sciences and Medical Sciences*, *58*(5), 453–460. https://doi.org/10.1093/gerona/58.5.m453

Hsu, W. (2014). Adaptive Postural Control for Joint Immobilization during Multitask Performance. *PLoS ONE*, *9*(10). https://doi.org/10.1371/journal.pone.0108667

Hsu, W. L., Chou, L. S., & Woollacott, M. (2013). Age-related changes in joint coordination during balance recovery. *Age (Dordrecht, Netherlands)*, *35*(4), 1299–1309. https://doi.org/10.1007/S11357-012-9422-X

Hsu, W. L., & Scholz, J. P. (2012). Motor abundance supports multitasking while standing. *Human Movement Science*, *31*(4), 844–862. https://doi.org/10.1016/j.humov.2011.07.017

Hughes, M. A., Weiner, D. K., Schenkman, M. L., Long, R. M., & Studenski, S. A. (1994). Chair rise strategies in the elderly. *Clinical Biomechanics*, *9*(3), 187–192. https://doi.org/10.1016/0268-0033(94)90020-5

Hughes, Michael A., Myers, B. S., & Schenkman, M. L. (1996). The role of strength in rising from a chair in the functionally impaired elderly. *Journal of Biomechanics*, *29*(12), 1509–1513. https://doi.org/10.1016/0021-9290(96)00083-8

Klous, M., Danna-Dos-Santos, A., & Latash, M. L. (2010). Multi-muscle synergies in a dual postural task: Evidence for the principle of superposition. *Experimental Brain Research*, *202*(2), 457–471. https://doi.org/10.1007/s00221-009-2153-2

Landers, M. R., Hatlevig, R. M., Davis, A. D., Richards, A. R., & Rosenlof, L. E. (2016). Does attentional focus during balance training in people with Parkinson’s disease affect outcome? A randomised controlled clinical trial. *Clinical Rehabilitation*, 30(1), 53-63. http://doi.org/10.1177/0269215515570377

Landers, M., Wulf, G., Wallmann, H., & Guadagnoli, M. (2005). An external focus of attention attenuates balance impairment in patients with Parkinson’s disease who have a fall history. *Physiotherapy*. https://doi.org/10.1016/j.physio.2004.11.010

Latash, M. L., & Huang, X. (2015). Neural control of movement stability: Lessons from studies of neurological patients. *Neuroscience*, *301*, 39–48. https://doi.org/10.1016/j.neuroscience.2015.05.075

Latash, M. L. (2008). *Synergy*. Oxford University Press.

Latash, M. L., Scholz, J. P., & Schöner, G. (2007). Toward a New Theory of Motor Synergies. *Motor Control*, *11*(3), 276–308. https://doi.org/10.1123/mcj.11.3.276

Latash, M. L., & Zatsiorsky, V. M. (2016). *Biomechanics and Motor Control*. Elsevier.

Latash, M. L., Scholz, J. P., & Schöner, G. (2002). Motor Control Strategies Revealed in the Structure of Motor Variability. *Exerc. Sport Sci. Rev, 30*(1), 26–31.

Lohse, K. R., Jones, M., Healy, A. F., & Sherwood, D. E. (2014). The role of attention in motor control. *Journal of Experimental Psychology: General*, *143*(2), 930–948. https://doi.org/10.1037/a0032817

Lohse, K. R., Sherwood, D. E., & Healy, A. F. (2010). Human Movement Science How changing the focus of attention affects performance , kinematics , and electromyography in dart throwing q. *Human Movement Science*, *29*(4), 542–555. https://doi.org/10.1016/j.humov.2010.05.001

Lord, S. R., Murray, S. M., Chapman, K., Munro, B., & Tiedemann, A. (2002). Sit-to-stand performance depends on sensation, speed, balance, and psychological status in addition to strength in older people. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *57*(8), M539–M543. https://doi.org/10.1093/gerona/57.8.m539

Mak, T. C. T., Young, W. R., Chan, D. C. L., & Wong, T. W. L. (2020). Gait Stability in Older Adults during Level-Ground Walking: The Attentional Focus Approach. *Journals of Gerontology - Series B Psychological Sciences and Social Sciences*, *75*(2), 274–281. https://doi.org/10.1093/geronb/gby115

Mak, T. C. T., Young, W. R., & Wong, T. W. L. (2021). Conscious Control of Gait Increases with Task Difficulty and Can Be Mitigated by External Focus Instruction. *Experimental Aging Research*, *47*(3), 288–301. https://doi.org/10.1080/0361073X.2021.1891811

Makizako, H., Shimada, H., Doi, T., Tsutsumimoto, K., Nakakubo, S., Hotta, R., & Suzuki, T. (2017). Predictive Cutoff Values of the Five-Times Sit-to-Stand Test and the Timed "Up & Go" Test for Disability Incidence in Older People Dwelling in the Community. *Physical Therapy*, *97*(4), 417–424. https://doi.org/10.2522/PTJ.20150665

Maurer, H., & Munzert, J. (2013). Influence of attentional focus on skilled motor performance: Performance decrement under unfamiliar focus conditions. *Human Movement Science*, *32*(4), 730–740. https://doi.org/10.1016/j.humov.2013.02.001

McNevin, N. H., Shea, C. H., & Wulf, G. (2003). Increasing the distance of an external focus of attention enhances learning. *Psychological Research*, 67(1), 22- 29. https://doi.org/10.1007/s00426-002-0093-6

McNevin, N. H., & Wulf, G. (2002). *Attentional focus on supra-postural tasks affects postural control*. *21*, 187–202. https://doi.org/10.1016/s0167-9457(02)00095-7

McNevin, N., Weir, P., & Quinn, T. (2013). Effects of attentional focus and age on suprapostural task performance and postural control. *Research Quarterly for Exercise and Sport*, *84*(1), 96–103. https://doi.org/10.1080/02701367.2013.762321

Monahan, C., & Hurley, W. (2021). Does instructing attentional focus direction affect static single leg balance performance? *International Journal of Sports Science & Coaching*. https://doi.org/https://doi.org/10.1177/17479541211058581

Morris, R., Lord, S., Bunce, J., Burn, D., & Rocherster, L. (2016). Gait and cognition: Mapping the global and discrete relationships in ageing and neurodegenerative disease. *Neuroscience and Biobehavioral Reviews*, *64*, 326–245. https://doi.org/10.1016/j.neubiorev.2016.02.012

Olafsdottir, H. B., Zatsiorsky, V. M., & Latash, M. L. (2008). The effects of strength training on finger strength and hand dexterity in healthy elderly individuals. *Journal of Applied Physiology*, *105*(4), 1166–1178. https://doi.org/10.1152/japplphysiol.00054.2008

Olafsdottir, H., Zhang, W., Zatsiorsky, V. M., & Latash, M. L. (2007). Age-related changes in multifinger synergies in accurate moment of force production tasks. *Journal of Applied Physiology*, *102*(4), 1490–1501. https://doi.org/10.1152/japplphysiol.00966.2006

Parr, R., & Button, C. (2009). End-point focus of attention: Learning the “Catch” in Rowing. *International Journal of Sports Psychology*, *40*(4), 616–635.

Pinto, V. A., Campolina, A. B., Mazoni, A. F., Mattos, D. J. S., & Vaz, D. V. (2020). Attention Focus Does Not Influence Performance of Sit-to-Stand in Young and Older Adults. *Journal of Motor Behavior*, *53*(1), 11–19. https://doi.org/10.1080/00222895.2020.1723477

Reisman, D. S., Scholz, J. P., & Schöner, G. (2002). Coordination underlying the control of whole body momentum during sit-to-stand. *Gait & Posture*, *15*(1), 45–55. https://doi.org/10.1016/S0966-6362(01)00158-8

Richer, N., Saunders, D., Polskaia, N., & Lajoie, Y. (2017). The effects of attentional focus and cognitive tasks on postural sway may be the result of automaticity. *Gait and Posture*, *54*, 45–49. https://doi.org/10.1016/j.gaitpost.2017.02.022

Rosenblatt, N. J., Eckardt, N., Kuhman, D., & Hurt, C. P. (2020). Older but not younger adults rely on multijoint coordination to stabilize the swinging limb when performing a novel cued walking task. Experimental brain research, 238(6), 1441–1454. https://doi.org/10.1007/s00221-020-05822-x

Sakurada, T., Hirai, M., & Watanabe, E. (2016). Optimization of a motor learning attention-directing strategy based on an individual’s motor imagery ability. *Experimental Brain Research*, *234*(1), 301–311. https://doi.org/10.1007/s00221-015-4464-9

Sakurada, T., Nakajima, T., Morita, M., Hirai, M., & Watanabe, E. (2017). Improved motor performance in patients with acute stroke using the optimal individual attentional strategy. *Scientific Reports*, *7*(December 2016), 1–10. https://doi.org/10.1038/srep40592

Scholz, J. P., Reisman, D., & Schöner, G. (2001). Effects of varying task constraints on solutions to joint coordination in a sit-to-stand task. *Experimental Brain Research*, *141*(4), 485–500. https://doi.org/10.1007/s002210100878

Scholz, J. P., & Schöner, G. (1999). The uncontrolled manifold concept: identifying control variables for a functional task. *Experimental Brain Research*, *126*(3), 289–306. https://doi.org/10.1007/S002210050738

Seidler, R. D., Bernard, J. A., Burutolu, T. B., Fling, B. W., Gordon, M. T., Gwin, J. T., Kwak, Y., & Lipps, D. B. (2010). Motor control and aging: Links to age-related brain structural, functional, and biochemical effects. *Neuroscience & Biobehavioral Reviews*, *34*(5), 721–733. https://doi.org/10.1016/j.neubiorev.2009.10.005

Shinohara, M., Scholz, J. P., Zatsiorsky, V. M., & Latash, M. L. (2004). Finger interaction during accurate multi-finger force production tasks in young and elderly persons. *Experimental Brain Research*, *156*(3), 282–292. https://doi.org/10.1007/S00221-003-1786-9

Thompson, L. D. V. (2009). Age-related muscle dysfunction. *Experimental Gerontology*, *44*(1–2), 106–111. https://doi.org/10.1016/j.exger.2008.05.003

Tinetti, M. E., Speechley, M., & Ginter, S. F. (1988). Risk factors for falls among elderly persons living in the community. *The New England Journal of Medicine*, *319*, 1701–1707. http://doi.org/10.1056/NEJM198812293192604

West, B. T., Welch, K. B., & Gałecki, A. T. (2015). *Linear Mixed Models: A practical guide using statistical software* (2nd ed.). Boca Raton, FL: Taylor & Francis.

Winter, D. A. (2009). Biomechanics and Motor Control of Human Movement. John Wiley & Sons

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: A review of an emerging area of research. *Gait and Posture*, *16*(1), 1–14. https://doi.org/10.1016/S0966-6362(01)00156-4

Wulf, G. (2013). Attentional focus and motor learning: A review of 15 years. In *International*

Review of Sport and Exercise Psychology. https://doi.org/10.1080/1750984X.2012.723728

Wulf, G., Mercer, J., McNevin, N., & Guadagnoli, M. A. (2004). Reciprocal influences of attentional focus on postural and suprapostural task performance. *Journal of Motor Behavior, 36*(2), 189–199. https://doi.org/10.3200/JMBR.36.2.189-199

Wulf, G., Weigelt, M., Poulter, D., & McNevin, N. (2003). Attentional focus on suprapostural tasks affects balance learning. *The Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, *56*(7), 1191–1211. https://doi.org/10.1080/02724980343000062

Yamada, T., & Demura, S. (2010). The relationship of force output characteristics during a sit-to-stand movement with lower limb muscle mass and knee joint extension in the elderly. *Archives of Gerontology and Geriatrics*, *50*(3), 46–50. https://doi.org/10.1016/j.archger.2009.05.009

Yogev-Seligmann, G., Sprecher, E., & Kodesh, E. (2017). The Effect of External and Internal Focus of Attention on Gait Variability in Older Adults. *Journal of Motor Behavior, 49*(2), 179–184. https://doi.org/10.1080/00222895.2016.1169983

Young, W. R., & Mark Williams, A. (2015). How fear of falling can increase fall-risk in older adults: applying psychological theory to practical observations. *Gait & Posture*, *41*(1), 7–12. https://doi.org/10.1016/j.gaitpost.2014.09.006

Young, W. R., Olonilua, M., Masters, R. S. W., Dimitriadis, S., & Mark Williams, A. (2016). Examining links between anxiety, reinvestment and walking when talking by older adults during adaptive gait. *Experimental Brain Research*, *234*(1), 161–172. https://doi.org/10.1007/S00221-015-4445-Z

Young, W. R., & Williams, A. M. (2014). Gait & Posture How fear of falling can increase fall-risk in older adults: Applying psychological theory to practical observations. *Gait & Posture*. https://doi.org/10.1016/j.gaitpost.2014.09.006

Zarghami, M., Saemi, E., & Fathi, I. (2012). External focus of attention enhances discus throwing performance. *Kinesiology*, *44*(1), 47–51.

Zhang, W., Scholz, J. P., Zatsiorsky, V. M., & Latash, M. L. (2008). What Do Synergies Do? Effects of Secondary Constraints on Multidigit Synergies in Accurate Force-Production Tasks. *Journal of Neurophysiology*, *99*(2), 500–513. https://doi.org/10.1152/jn.01029.2007

Appendix 1: UCM Analysis

The angles for ankle, knee, hip, lumbar spine, thoracic spine, cervical spine, atlanto-occipital, sternoclavicular, shoulder, elbow, wrist and hand-cup (the angle between the vector from the 2nd metacarpophalangeal to the wrist joint and the vector between the two markers in the cup) were defined in the sagittal plane. Control variables that were expected to be stabilized by co-variation of joint angles during STS were defined. The vertical and horizontal position of the CoM in the sagittal plane were the two main control variables (Scholz et al., 2001; Scholz & Schöner, 1999). The bidimensional cup position in the sagittal plane was also considered a potentially stabilized control variable. Geometric models linking joint angle changes to control variable changes were defined with the angles: θ1= ankle, θ2= knee, θ3= hip, θ4= lumbar spine, θ5= thoracic spine, θ6= cervical spine, θ7= atlanto-occipital, θ8= sternoclavicular, θ9= shoulder, θ10= elbow, θ11= wrist, and θ12= hand-cup.

A. Geometric model relating horizontal Cup horizontal position (*Cup hor*) to joint configuration space:

$$
\begin{aligned}
&Cup\ \mathrm{h}or = l1\cos(\theta 1) + l2\ cos(\theta 1 + \theta 2) + l3\cos(\theta 1 + \theta 2 + \theta 3) \\
&+l4\cos(\theta 1+\theta 2+\theta 3+\theta 4)+l5\cos(\theta 1+\theta 2+\theta 3+\theta 4+\theta 5)\ +l8\cos(\theta 1+\theta 2+\theta 3+\theta 4+\theta 5+\theta 8) \\
&+l9\cos(\theta 1+\theta 2+\theta 3+\theta 4+\theta 5+\theta 8+\theta 9)\ +l10\cos(\theta 1+\theta 2+\theta 3+\theta 4+\theta 5+\theta 8+\theta 9+\theta 10) \\
&+l11\cos(\theta 1+\theta 2+\theta 3+\theta 4+\theta 5+\theta 8+\theta 9+\theta 10+\theta 11) \\
&+l12\cos(\theta 1+\theta 2+\theta 3+\theta 4+\theta 5+\theta 8+\theta 9+\theta 10+\theta 11+\theta 12)
\end{aligned}
$$

B. Geometric model relating horizontal Cup vertical position (*Cup vrt*) to joint configuration space:

$$
\begin{aligned}
&Cup\ vrt = l1\ sin\ (\theta 1) + l2\ sin(\theta 1 + \theta 2) + l3\sin(\theta 1 + \theta 2 + \theta 3) \\
&+l4\sin(\theta 1+\theta 2+\theta 3+\theta 4)+l5\sin(\theta 1+\theta 2+\theta 3+\theta 4+\theta 5)\ +l8\sin(\theta 1+\theta 2+\theta 3+\theta 4+\theta 5+\theta 8) \\
&+l9\sin(\theta 1+\theta 2+\theta 3+\theta 4+\theta 5+\theta 8+\theta 9)\ +l10\sin(\theta 1+\theta 2+\theta 3+\theta 4+\theta 5+\theta 8+\theta 9+\theta 10)
\end{aligned}
$$

$+l11\sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta8+\theta9+\theta10+\theta11)$
$+l12\sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta8+\theta9+\theta10+\theta11+\theta12)$

C. Geometric model relating horizontal CoM position (*CoM hor*) to joint configuration space

$COM\ hor = origin\ pos\ hor + m1(l1\cos(\theta1)\ r1)$
$+ m2(l1\cos(\theta1) + l2\cos(\theta1+\theta2)\ r2)$
$+m3(l1\cos(\theta1)+l2\cos(\theta1+\theta2)+l3\cos(\theta1+\theta2+\theta3)r3)$
$+m4(l1\cos(\theta1)+l2\cos(\theta1+\theta2)+l3\cos(\theta1+\theta2+\theta3) +l4(\theta1+\theta2+\theta3+\theta4)r4)$
$+ m5(l1\cos(\theta1) + l2\cos(\theta1+\theta2)$
$+l3\cos(\theta1+\theta2+\theta3)+l4cos(\theta1+\theta2+\theta3+\theta4)+l5cos(\theta1 +\theta2+\theta3+\theta4+\theta5)r5)$
$+ m6\ (l1\cos(\theta1)$
$+ l2\cos(\theta1+\theta2) +l3\cos(\theta1+\theta2+\theta3)+l4cos(\theta1+\theta2+\theta3+\theta4)+l5cos(\theta1$
$+\theta2+\theta3+\theta4+\theta5)+l6cos(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6)r6) + m7(l1\cos(\theta1)$
$+ l2\cos(\theta1+\theta2) +l3\cos(\theta1+\theta2+\theta3)+l4cos(\theta1+\theta2+\theta3+\theta4)+l5cos(\theta1$
$+\theta2+\theta3+\theta4+\theta5)+l6cos(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6)$
$+l7\cos(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7)r7)$
$+ m8(l1\cos(\theta1)$
$+ l2\cos(\theta1+\theta2) +l3\cos(\theta1+\theta2+\theta3)+l4cos(\theta1+\theta2+\theta3+\theta4)+l5cos(\theta1$
$+\theta2+\theta3+\theta4+\theta5)+l8\cos(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7 + \theta8)r8)$
$+ m9(l1\cos(\theta1)$
$+ l2\cos(\theta1+\theta2) +l3\cos(\theta1+\theta2+\theta3)+l4cos(\theta1+\theta2+\theta3+\theta4)+l5cos(\theta1$
$+\theta2+\theta3+\theta4+\theta5)+l8\cos(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7$
$+\theta8)+l9\cos(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7+\theta8+\theta9)r9)$
$+m10(l1\cos(\theta1)$
$+ l2\cos(\theta1+\theta2)$
$+l3\cos(\theta1+\theta2+\theta3)+l4cos(\theta1+\theta2+\theta3+\theta4)+l5cos(\theta1$
$+\theta2+\theta3+\theta4+\theta5)+l8\cos(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7$
$+\theta8)+l9\cos(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7+\theta8+\theta9)$
$+l10\cos(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7+\theta8+\theta9+\theta10)r10) + m11(l1\cos(\theta1)$
$+ l2\cos(\theta1+\theta2) +l3\cos(\theta1+\theta2+\theta3)+l4cos(\theta1+\theta2+\theta3+\theta4)+l5cos(\theta1$
$+\theta2+\theta3+\theta4+\theta5)+l8\cos(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7$
$+\theta8)+l9\cos(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7+\theta8+\theta9)$
$+l10\cos(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7+\theta8+\theta9+\theta10)$
$+l11\cos(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7+\theta8+\theta9+\theta10$
$+ \theta11)r11)$

C. Geometric model relating vertical CoM position (*CoM vrt*) to joint configuration space:

$$\begin{aligned}
&COM\ vrt = origin\ pos\ vrt + m1(l1\,\sin(\theta1)\ r1)\\
&+ m2(l1\,\sin(\theta1) + l2\,\sin\,(\theta1 + \theta2)\ r2)\\
&+m3(l1\sin(\theta1)+l2\sin(\theta1+\theta2)+l3\sin(\theta1+\theta2+\theta3)r3)\\
&+m4(l1\sin(\theta1)+l2\sin(\theta1+\theta2)+l3\sin(\theta1+\theta2+\theta3)\ +l4 sin(\theta1+\theta2+\theta3+\theta4)r4)\\
&+ m5(l1\,\sin(\theta1) + l2\,\sin(\theta1 + \theta2)\\
&+l3\sin(\theta1+\theta2+\theta3)+l4 sin(\theta1+\theta2+\theta3+\theta4)+l5 sin(\theta1\ +\theta2+\theta3+\theta4+\theta5)r5)\\
&+m6\ (l1\,\sin(\theta1)\\
&+ l2\,\sin(\theta1 + \theta2)\\
&+l3\sin(\theta1+\theta2+\theta3)+l4 sin(\theta1+\theta2+\theta3+\theta4)+l5 sin(\theta1\\
&+\theta2+\theta3+\theta4+\theta5)+l6 sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6)r6) + m7(l1\,\sin(\theta1)\\
&+ l2\,\sin(\theta1 + \theta2)\ +l3\sin(\theta1+\theta2+\theta3)+l4 sin(\theta1+\theta2+\theta3+\theta4)+l5 sin(\theta1\\
&+\theta2+\theta3+\theta4+\theta5)+l6 sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6)\\
&+l7\sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7)r7)\\
&+ m8(l1\,\sin(\theta1)\\
&+ l2\,\sin(\theta1 + \theta2)\ +l3\sin(\theta1+\theta2+\theta3)+l4 sin(\theta1+\theta2+\theta3+\theta4)+l5 sin(\theta1\\
&+\theta2+\theta3+\theta4+\theta5)+l8\sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7\ +\ \theta8)r8)\\
&+ m9(l1\,\sin(\theta1)\\
&+ l2\,\sin(\theta1 + \theta2)\ +l3\sin(\theta1+\theta2+\theta3)+l4 sin(\theta1+\theta2+\theta3+\theta4)+l5 sin(\theta1\\
&+\theta2+\theta3+\theta4+\theta5)+l8\sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7\\
&+\theta8)+l9\sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7+\theta8+\theta9)r9)\\
&+ m10(l1\,\sin(\theta1)\\
&+ l2\,\sin(\theta1 + \theta2)\ +l3\sin(\theta1+\theta2+\theta3)+l4\sin(\theta1+\theta2+\theta3+\theta4)+l5 sin(\theta1\\
&+\theta2+\theta3+\theta4+\theta5)+l8\sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7\\
&+\theta8)+l9\sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7+\theta8+\theta9)\\
&+l10\sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7+\theta8+\theta9+\theta10)r10) + m11(l1\,\sin(\theta1)\\
&+ l2\,\sin(\theta1 + \theta2)\ +l3\sin(\theta1+\theta2+\theta3)+l4\sin(\theta1+\theta2+\theta3+\theta4)+l5 sin(\theta1\\
&+\theta2+\theta3+\theta4+\theta5)+l8\sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7\\
&+\theta8)+l9\sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7+\theta8+\theta9)\\
&+l10\sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7+\theta8+\theta9+\theta10)\\
&+l11\sin(\theta1+\theta2+\theta3+\theta4+\theta5+\theta6+\theta7+\theta8+\theta9+\theta10\\
&+\ \theta11)r11)
\end{aligned}$$

origin pos hor is the horizontal position of the origin, i.e. the ankle, *origin post vrt* is the vertical position of the origin, i.e. the ankle, *li* is the segment length where i={shank, thigh, pelvis, lower trunk, upper trunk, neck, head, clavicle, upper arm, forearm, hand, hand-cup, great trochanter to acromion}, *mi* is the mass proportion of the segment, *ri* is the length proportion of the segment CoM to distal reference point, and *θi* is the angle between segments.

Finally, projections of variance in the space of elemental variables onto the UCM (V_{UCM}) and onto its orthogonal complement (V_{ORT}) were calculated. Magnitudes of V_{UCM} and V_{ORT} were normalized by the number of dimensions in the corresponding subspaces so they could be compared quantitatively. V_{UCM} and V_{ORT} were calculated at every time frame of STS. The integral of each measure was computed for each of the three STS phases.

Figure 1

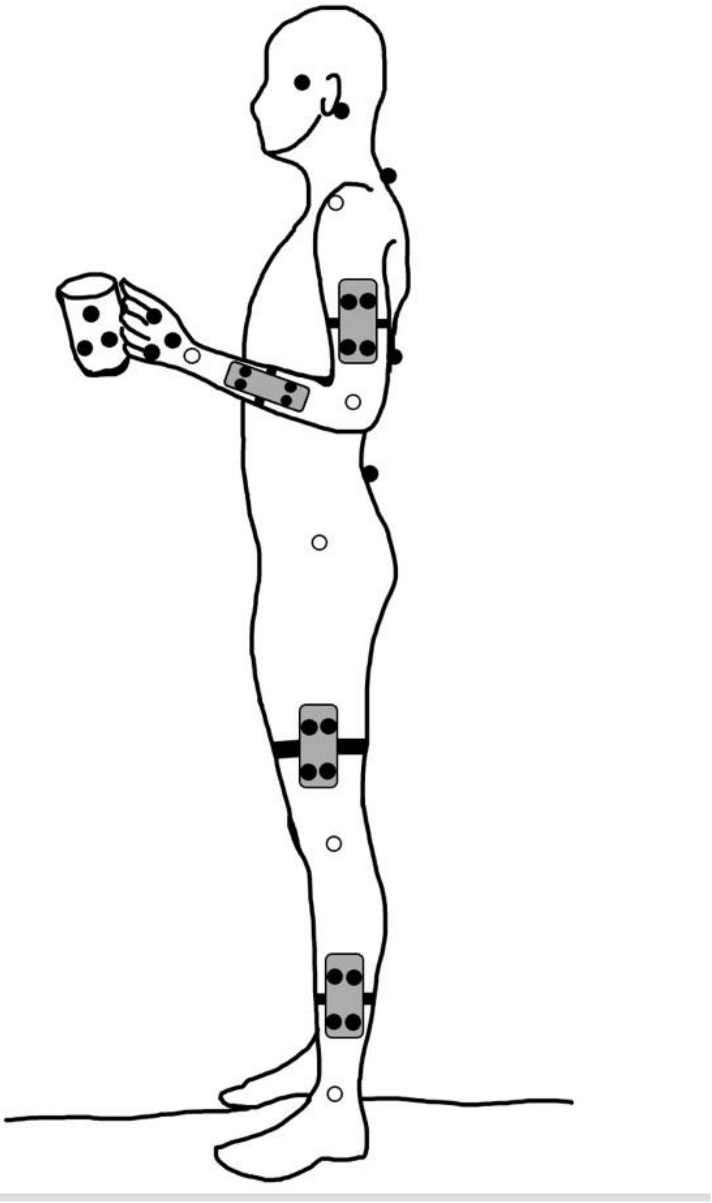


Figure 2

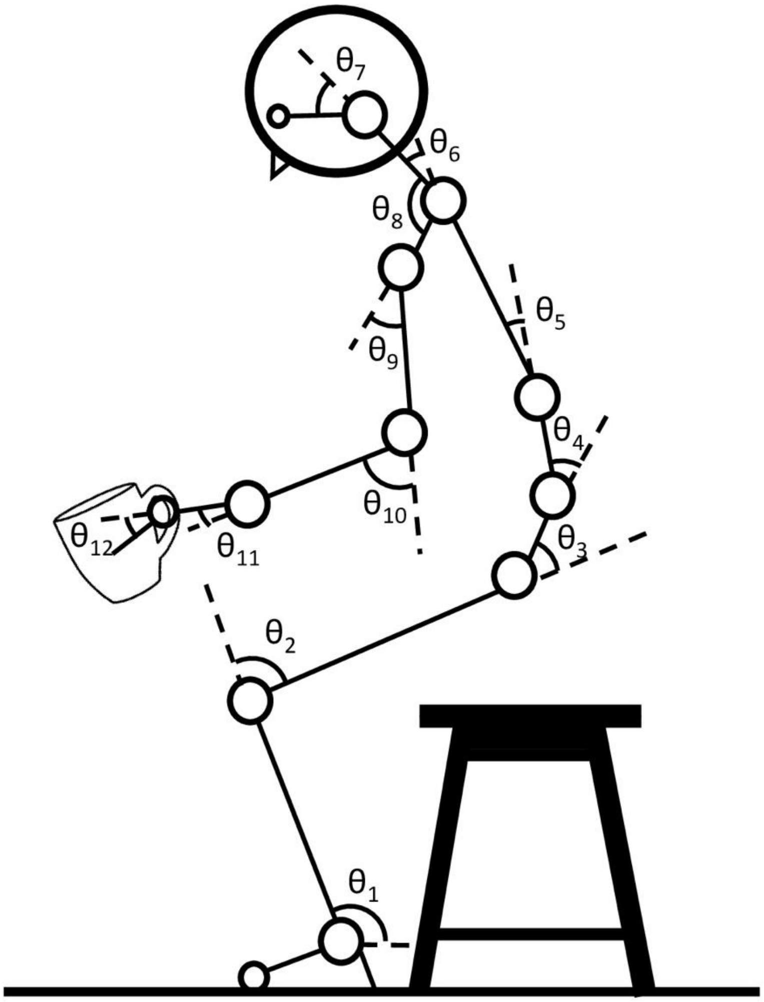

θ_7
θ_6
θ_8
θ_5
θ_9
θ_4
θ_{10}
θ_3
θ_{12}
θ_{11}
θ_2
θ_1

Figure 3

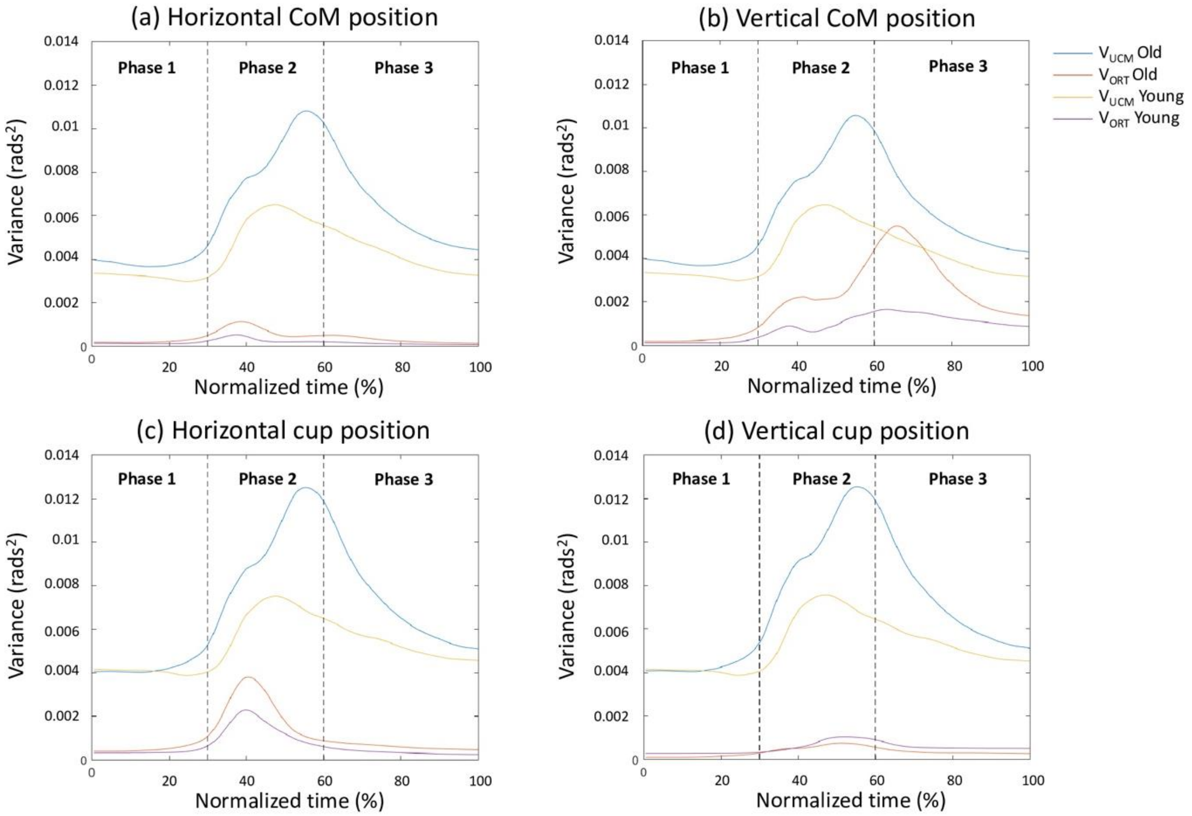

(a) Horizontal CoM position
(b) Vertical CoM position
(c) Horizontal cup position
(d) Vertical cup position
Phase 1
Phase 2
Phase 3
Variance (rads^2)
Normalized time (%)
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0
20
40
60
80
100
V_{UCM} Old
V_{ORT} Old
V_{UCM} Young
V_{ORT} Young

Figure 4

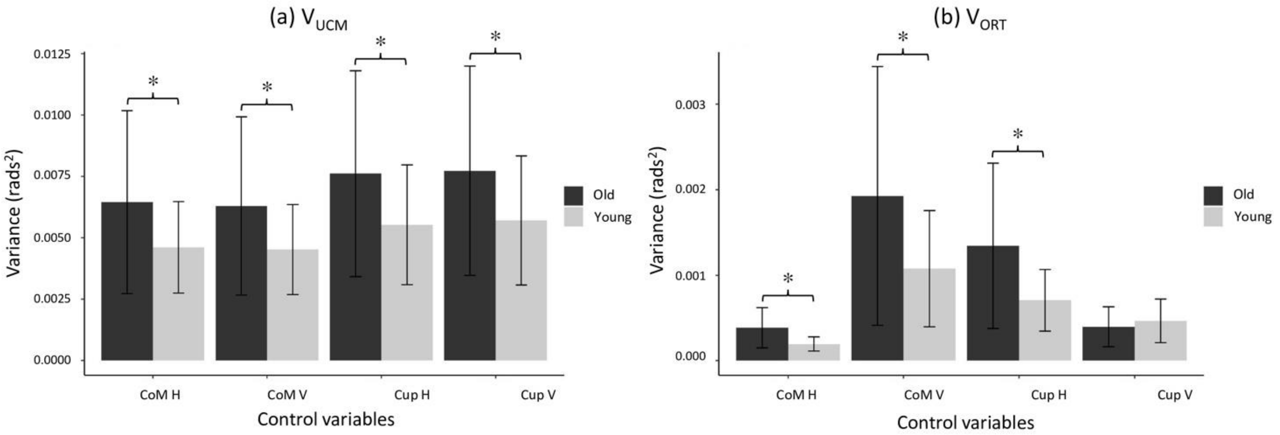
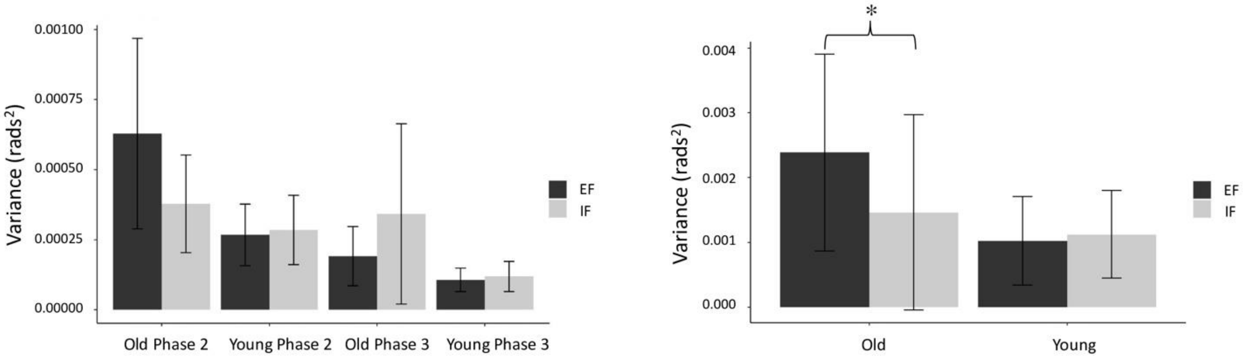

(a) V_{UCM}
Variance (rads^2)
0.0125
0.0100
0.0075
0.0050
0.0025
0.0000
*
*
*
*
CoM H
CoM V
Cup H
Cup V
Control variables
Old
Young
(b) V_{ORT}
Variance (rads^2)
0.003
0.002
0.001
0.000
*
*
*
CoM H
CoM V
Cup H
Cup V
Control variables
Old
Young

Figure 5

(a) V_{ORT} for horizontal CoM position

(b) V_{ORT} for vertical CoM position



(c) V_{ORT} for horizontal cup position

(d) V_{ORT} for vertical cup position

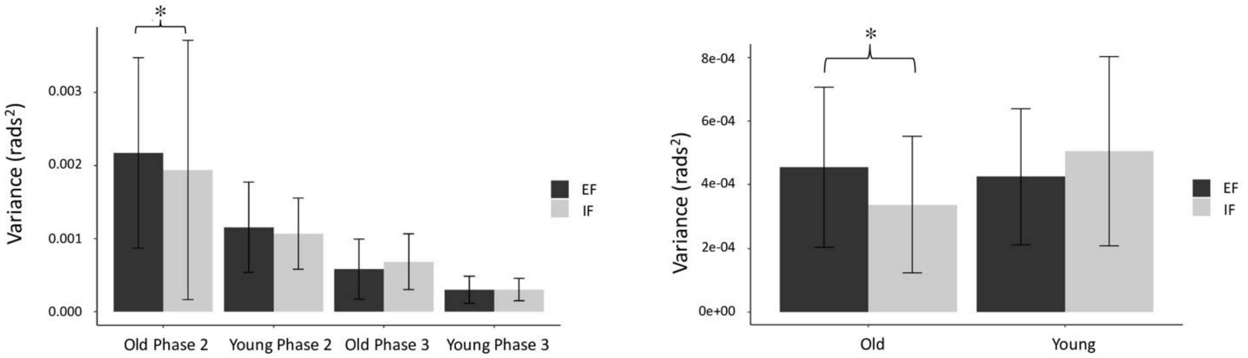


Figure 1. Schematic of the experimental set-up with clusters, active markers (filled circles) and virtual markers (empty circles).

Figure 2. Geometric model linking joint angles to changes in the control variables. The 12 angles used in the Jacobian matrices were (from Θ_1 to Θ_{12}): ankle, knee, hip, lumbar-spine, thoracic-spine, cervical-spine, atlanto-occipital, sternoclavicular, shoulder, elbow, wrist, and hand-cup angle.

Figure 3. Average V_{UCM} and V_{ORT} values over time as a function of age for (**a**) horizontal and (**b**) vertical CoM positions, and (**c**) horizontal and (**d**) vertical cup positions.

Figure 4. Mean (**a**) V_{UCM} and (**b**) V_{ORT} values for the horizontal and vertical CoM and cup positions as a function of age. Asterisk (*) indicates $p < .05$. Error bars represent standard deviation of the mean. H = horizontal; V = vertical.

Figure 5. Mean V_{ORT} values for (**a**) the horizontal CoM and (**c**) cup positions as a function of focus of attention, age, and movement phase; and mean V_{ORT} values for (**b**) the vertical CoM and (**d**) cup positions as a function of focus of attention and age. Asterisk (*) indicates $p < .05$. Error bars represent standard deviation of the mean.