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Age-related differences in movement strategies and postural control during stooping and crouching tasks

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ABSTRACT

While epidemiologic data suggests that one in four older adults have difficulty performing stooping and crouching (SC) tasks, little is known about how aging affects SC performance. This study investigated differences between young and older adults in lower limb kinematics and underfoot center of pressure (COP) measures when performing a series of SC tasks. Twelve healthy younger and twelve healthy older participants performed object-retrieval tasks varying in: (1) initial lift height, (2) precision demand, and (3) duration. Whole-body center of mass (COM), underfoot COP, and hip and knee angular kinematics (maximum angles and velocities) were analyzed. Compared to younger, older participants moved slower when transitioning into and out of pick-up postures that were characterized by less hip and knee flexion. Older participants also showed a diminished ability to adapt to the changing postural demands of each set of tasks. This was especially evident during longer tasks, whereby older individuals avoided high knee flexion crouching postures that were commonly used by younger participants. Older adults also tended to exhibit faster and more frequent COP trajectory adjustments in the anterior–posterior direction. It is likely that limitations in physical characteristics such as lower limb strength and range of motion contributed to these differences.

1. Introduction

Age-related deterioration of muscle strength, range of motion (ROM), and motor coordination can lead to functional decline in older adults (Bassey et al., 1992; Janssen, Heymsfield, & Ross, 2002; Petrella, Miller, & Cress, 2004). Individuals in a state of functional decline may in turn suffer a loss of independence as they begin relying on help from formal (paid) and informal (unpaid) caregivers to perform activities such as bathing, eating, and transferring from one posture to another (Dunlop, Hughes, & Manheim, 1997). Stooping and crouching (SC) movements are integral to many daily tasks such as reaching to low shelves and retrieving items from the floor. Stooping involves bending primarily at the waist with little to no flexion in the knees and feet flat on the floor. Crouching, as defined for this study, consists of high knee flexion with only the forefeet contacting the support surface, the heels raised above the floor, and the buttocks effectively resting on the calf region. As movements involving these postures require significant coordination, strength, and flexibility, they provide an interesting scenario for evaluating age-related changes in functional task performance (Hernandez, Ashton-Miller, & Alexander, 2013). While epidemiologic data suggests that 24% of community-dwelling older adults report significant difficulty or complete inability to perform SC movements (Taylor, Wallace, Ostfeld, & Blazer, 1997), few studies have demon-

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strated how aging affects the manner in which such tasks are performed. As older demographics continue to grow in developed countries (Seidel et al., 2009; Statistics Canada, 2010), our understanding of how aging affects SC ability must improve in order to properly guide intervention strategies aimed at curtailing functional decline.

Volitional movements involving high degrees of hip, knee, and ankle flexion can be challenging for older adults. Such movements require an individual to coordinate whole body balance with a changing postural configuration, often while he or she is performing a goal-oriented task such as grasping an object (Hernandez, Goldberg, & Alexander, 2010; Long & Pavalko, 2004). Recent work investigating age-related differences during controlled squat-to-reach tasks suggests that older adults tend to move slower than younger adults and position themselves higher above the floor (Hernandez et al., 2013; Kuo, Kao, Chen, & Hong, 2011). Interestingly, older adults use a greater proportion of their available muscle capacity when performing these, and many other, functional tasks (Hortobagyi, Mzelle, Beam, & DeVita, 2003; Kuo et al., 2011; Madhavan, Burkart, Baggett, et al., 2009). In a similar experiment, Hernandez et al. (2013) found that while older adults' maximum floor-level forward reach distances were, on average, 22% shorter than young participants', they used self-selected base of support (BOS) areas that were 50% larger. This trend of older adults moving slower through shorter vertical distances while employing a larger BOS – and using a greater proportion of their available muscle capacity – may reflect an attempt to minimize the risk of compromising balance and initiating a fall (Hernandez, Ashton-Miller, & Alexander, 2012; Long & Pavalko, 2004; O'Loughlin, Robitaille, Boivin, & Suissa, 1993).

Examining differences in balance control measures during SC tasks may provide further insight into the process of age-related SC deterioration. Existing works, while not focusing on SC tasks specifically, have noted age-related declines in COP trajectory smoothness during forward reach tasks (Huang & Brown, 2013), and increases in the frequency of COP adjustments during targeted movements (Hernandez et al., 2012). These measures have been used to detect and quantify changes in coordination during volitional movements, and can likely be extended to SC tasks (Hass, Waddell, Wolf, Juncos, & Gregor, 2008; Hernandez et al., 2012; Huang & Brown, 2013). Of particular relevance to the current study is a recent finding that, during forward reaches to various heights, lower targets elicited the greatest age-related differences, with 60% higher 'jerk' scores (a measure of COP trajectory smoothness) in older compared to younger participants (Huang & Brown, 2013). When only the feet are in contact with the ground – as is the case during SC movements – the goal of the balance control system is to regulate the COM location by using muscles crossing the hip and ankle to alter COP location (Winter, 1995). Thus, evaluating the velocity and frequency of COP adjustments as they relate to the anterior–posterior (AP) position of the COM may add value to existing COP-based trajectory smoothness measures such as those outlined above (Hernandez et al., 2012; Huang & Brown, 2013). We propose two dynamic postural control measures that incorporate the COM and relate to trajectory smoothness: (1) mean COP to COM velocity ratio (*VelRatio*), and (2) the frequency with which the COP crosses over the COM (*CrossRate*). *VelRatio* provides a useful comparator between the controlled variable (COM) and the controlling variable (COP) during fixed support movement scenarios (Winter, 1995). A more efficient postural control system should trend toward a lower *VelRatio*, indicating that the COP does not have to move disproportionately faster than the COM in order to control its position (Winter, 1995). A lower *VelRatio* could also indicate than an individual is more adept at using information pertaining to their body (COM) sway velocity, previously identified as important for upright posture (Jeka, Kiemel, Creath, Horak, & Peterka, 2004; Masani, Popovic, Nakazawa, Kouzaki, & Nozaki, 2003), in order to guide appropriate motor strategies via changes to their COP. *CrossRate* similarly provides a measure of the efficiency of control, but specifically quantifies the frequency with which the COP crosses the COM in order to adjust the trajectory of the COM toward a stable equilibrium state (Winter, 1995).

The majority of SC research to date has involved important controls such as experimenter-defined postures (e.g., standardized foot separation distance) and specified movement speeds (DiDomenico, McGorry, & Banks, 2011; Hernandez et al., 2013; Kuo et al., 2011). While recognizing the contributions of these approaches, we feel there is additional value in observing potential age-related differences during unconstrained SC tasks that resemble those naturally encountered in daily life. Such data may improve our understanding of how aging affects SC task performance, and potentially highlight the role of specific task parameters (e.g., duration required to complete a pick-up task) in guiding movement strategies. Accordingly, our objective was to assess the influence of aging on SC task performance by comparing vertical COM and lower limb kinematics, and underfoot COP and COM velocity and trajectory adjustment measures between younger and older participants during tasks that differed in: (1) initial lift height, (2) precision demand, and (3) duration.

We hypothesized that, in all tasks, older participants would move slower than younger participants and employ pick-up postures that were more 'upright'. This would be demonstrated by comparatively lower hip and knee flexion velocities in older adults, which would lead to lower COM vertical velocities during transitions to and from postures used to retrieve the object(s). Older adults' more upright postures would be characterized by lower maximum hip and knee flexion values – resulting in a higher whole-body vertical COM position at the moment of object retrieval. This prediction is based on the supposition that because older participants would likely have decreased lower extremity strength (Hernandez et al., 2010), they would avoid high knee flexion crouching postures from which it may be difficult to stand back up (Hughes & Schenkman, 1996). We further hypothesized that, in all tasks, older participants would demonstrate a higher rate of COP to COM crossings, and a higher COP to COM velocity ratio, reflecting a greater propensity to adjust the trajectory of their COP throughout the movement (Hernandez et al., 2012; Huang & Brown, 2013), which likely corresponds to a heightened attempt at controlling COM location. Finally, we predicted that as tasks became more challenging through: (1) lower initial lift height, (2) increased precision demand, and (3) longer duration, age-related differences in kinematic and COP and COM trajectory measures would increase, reflecting a diminished ability in older adults to appropriately adapt to the changing task demands.

2. Methods

2.1. Participants

The study population consisted of twelve healthy young (aged 18–26 years) and twelve healthy community-dwelling older (aged 63–85 years) adults, with six males and six females in each group (Table 1). Young participants were recruited from the University of Waterloo student population, while older participants were drawn primarily from the Waterloo Research in Aging Participant Pool. All participants were interviewed prior to participation to ensure they had no anatomical, neurological, or cognitive impairments that might affect their mobility. Participants were also screened to ensure they were able to perform SC tasks, were not using any psychotropic medications, had no prosthetics or joint replacements, and did not use ambulatory aids. All participants provided informed written consent as approved by the Office of Research Ethics at the University of Waterloo.

2.2. Instrumentation

Four Optotrak Certus motion capture banks, utilizing 12 cameras in total (Northern Digital, Inc., Waterloo, ON, Canada) were used to track kinematic data. Infrared light-emitting diode markers, arranged in clusters of four, were placed on the left side of the head, posterior aspects of the sacrum and thorax, and bilaterally on the feet, lower legs, thighs, upper arms, and lower arms. Individual markers were also placed on the third metacarpal head of each hand. A digitizing probe was used to identify relevant anatomical landmarks, which defined the segment endpoints corresponding to each marker cluster. All activities were performed while standing on a force platform (46.4 cm × 50.8 cm, Model OR6-7-2000, Advanced Medical Technology, Inc., Watertown, MA, USA) embedded in the laboratory floor. Kinematic and kinetic data were sampled at 32 and 512 Hz, respectively. Isometric peak torques for the knee extensors and flexors were evaluated using a Cybex II dynamometer (Cybex International Inc., Medway, MA, USA) and collected at 512 Hz. Passive ROM about the flexion/extension axes of the dominant hip and knee were assessed using a Leighton flexometer.

2.3. Protocol

Participants performed a series of tasks that required them to lower their COM from standing in order to retrieve one or more object(s) before returning to standing. The tasks, depicted in Fig. 1, differed in: (1) initial lift height, (2) precision required, and (3) duration. For the initial lift height condition, participants were instructed to pick up a round, 3.5 cm diameter plastic chip from the following heights using their dominant hand: floor level, 10%, 20%, 30%, 40%, and 50% of greater trochanter height. The precision demand was modified by having participants pick up a plastic dustpan from the floor instead of the chip. Due to the large, easy-to-grasp handle of the dustpan, this task required a lower degree of fine motor control, and thus less precision, compared to the small plastic chip. Finally, we increased task duration by increasing the number of chips that had to be retrieved from the floor. In this series of bimanual tasks, participants held a paper cup in their non-dominant hand while using their dominant hand to individually grasp 1, 4, 8, or 12 chips from the floor and place them into the cup, before returning to a standing position. For single object and the 4 chip bimanual tasks, the objects were placed approximately 20 cm in front of the participant's toes. This was deemed a comfortable distance that prevented participants from reaching forward excessively or employing awkward postures needed to retrieve objects too close to their feet. For the 8 and 12 chip bimanual tasks, the chips were spaced evenly and arranged in rows of 4, with the closest row approximately 15 cm, and the farthest approximately 25 cm, in front of the participant's toes. Participants were instructed to complete the tasks at their own, comfortable pace; the only requirement was that their feet remain on the force platform at all times and they stand quietly before and after completing each task. Participants removed their footwear and wore tight-fitting, flexible shorts and a lightweight shirt for all trials. Task order was randomized, with participants completing each task only once to capture natural movements not influenced by previous trials.

Table 1
Mean (SD) participant characteristics.

	Young participants (n = 12)	Older participants (n = 12)
Mean age (y)[a]	22.8 (2.4)	69.5 (6.9)
Height (m)	1.73 (0.1)	1.75 (0.1)
Mass (kg)[a]	73.5 (15.6)	87.6 (16.4)
Body mass index (kg/m^2)[a]	24.3 (2.8)	28.4 (4.2)

[a] Indicates significant age-effect ($p < 0.05$).

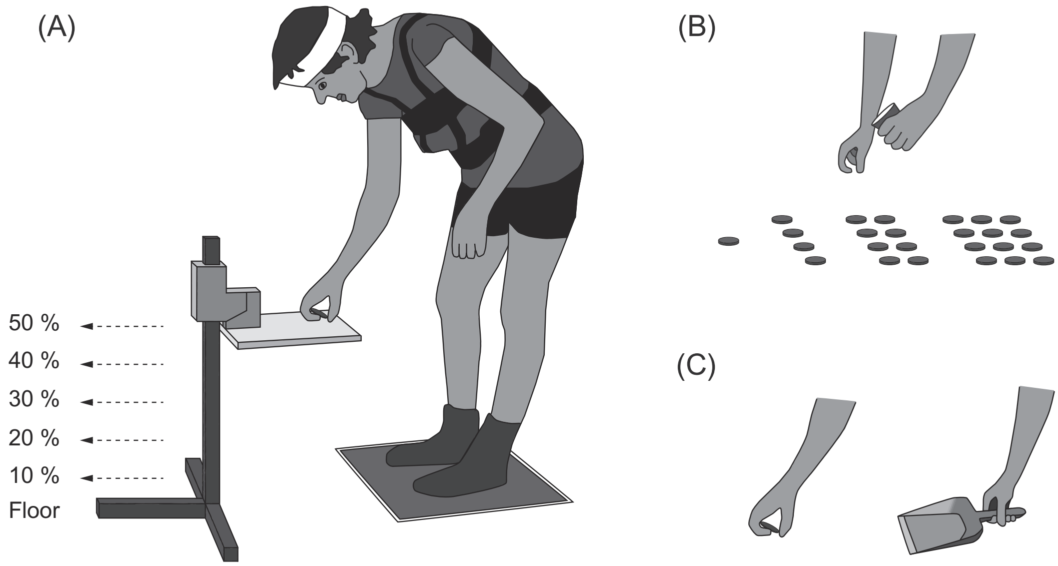

Fig. 1. Depiction of the three stooping and crouching task conditions. Tasks are meant to become more challenging as: (A) shelf height is lowered toward the floor; (B) duration increases when more chips must be retrieved; and (C) precision demands increase when retrieving the chip compared to the dustpan.

After the SC tasks were completed, we assessed the isometric strength and passive ROM of each participant's dominant leg. Isometric peak torque of the knee flexion/extension musculature was evaluated as described in a previous study by Hernandez et al. (2010) and normalized to body weight (Bohannon, 2009). Passive ROM about the flexion/extension axes of the hip and knee were measured using a Leighton flexometer according to the guidelines described in MacDougall, Wenger, and Green (1991).

2.4. Data processing and analysis

All raw marker and force platform data were processed using custom Visual3D pipelines (Visual3D v4, C-Motion, Germantown, MD, USA). Data points containing occluded marker signals were interpolated using a cubic spline algorithm (Howarth & Callaghan, 2010). Fourth order, zero-lag, low-pass Butterworth filters with cutoff frequencies of 10 Hz for force plate and 4 Hz for marker data were then applied to attenuate high-frequency noise in each signal. Whole body COM was derived from a 15-segment rigid-link model, with segment masses and COM positions estimated using de Leva's body segment parameters (de Leva, 1996). Horizontal whole-body COM and force plate-derived COP positions were spatially synchronized such that their mean positions were equivalent in the AP direction. This accounted for any COM position offset originating from the anthropometric model. Joint flexion/extension angles were calculated for the left knee and the hip (spanned by segments representing the thorax and left thigh). Ankle kinematics were analyzed in a previous work (Glinka, 2013), but excluded from the current study to minimize redundancy as age and task-related results were similar in the ankle compared to the knee and hip. Joint angular and COM vertical velocities were then calculated using a finite-difference technique. These temporal data representing joint angular, whole body COM, and underfoot COP positions were then exported to Matlab (MATLAB r2011b, Mathworks Inc., Natick, MA, USA).

Each trial was divided into distinct movement phases: the downward transition from standing to the pick-up posture and the transition upwards from this posture to standing. The static portion of each task was not analyzed in the current study. The onset and end of each movement was defined using the vertical velocity of the vertex (top of head) and a 5% of maximum velocity threshold, as outlined in previous works (Hernandez et al., 2013; Teasdale, Bard, Fleury, Young, & Proteau, 1993). Maximum knee and hip angles, and minimum vertical COM position, were calculated for each trial to describe the posture at the moment of object retrieval. Maximum joint angular and vertical COM velocities were also obtained to describe the speed of movement during transitions down to and back up from postures used to complete each task. Additionally, we monitored the vertical positions of the calcaneus markers to determine if participants were lifting their heels and employing a smaller, forefoot BOS (Hernandez et al., 2013; Kuo et al., 2011). To describe dynamic COM control within the context of COP trajectory adjustments (Hass et al., 2008; Hernandez et al., 2012; Huang & Brown, 2013), we calculated the frequency with which the COP crossed over the COM (*CrossRate*) and the ratio of the COP to COM mean velocities (*VelRatio*) for each trial, from the onset to the end of the movement, once participants returned to standing. Both measures were calculated for the AP direction.

2.5. Statistics

Assumptions of normality were confirmed using the Shapiro–Wilk test for each dependent variable. Independent *t*-tests were performed to assess differences in age, height, weight, BMI, isometric strength, and passive ROM between young and older participants. Mixed-model repeated measures ANOVAs were conducted for each kinematic and balance control measure to investigate main effects of age and task condition (initial lift height, precision, and duration), as well as potential interactions between these variables. Post-hoc tests were not evaluated in cases where main effects were significant, as the purpose of this work was to assess general age and task-related differences and the presence of interactions. Additional work could address these issues towards determining specific task-demand conditions at which potentially significant age-related differences emerge. The Fisher exact test was used to investigate group differences in BOS (flatfoot versus forefoot). All analyses were performed with statistical analysis software (SPSS Version 18.0, SPSS Inc., Chicago, IL, USA) using a significance level of $\alpha = 0.05$.

3. Results

Older participants exhibited 30% lower knee extensor and 31% lower knee flexor torques compared to young participants ($p < 0.05$; Table 2). Passive hip extension and knee flexion ROM values were also significantly lower (28% and 11%, respectively) in older participants ($p < 0.05$; Table 2).

3.1. Movement speed and posture

In all three conditions (initial lift height, precision required, and duration), older participants moved significantly slower than younger participants when transitioning into and out of postures used to retrieve the required object(s). This trend was characterized by comparatively lower maximum knee and hip angular velocities, which led to slower whole body COM vertical velocities (Fig. 2; Table 3). Specifically, during the downward transition phase, maximum vertical COM velocities were slower in the older cohort by 28% during the varying lift height tasks (0.28 (SD = 0.10) m/s versus 0.39 (0.17) m/s; $p = 0.001$), 29% during the varying precision tasks (0.39 (0.08) m/s versus 0.55 (0.14) m/s; $p = 0.001$), and 26% during the varying duration tasks (0.42 (0.09) m/s versus 0.56 (0.16) m/s; $p = 0.008$). Significant ordinal interactions were observed for maximum COM vertical velocity and maximum hip angular velocity during the varying lift height (COM vertical velocity: $p < 0.001$; hip angular velocity: $p = 0.034$) and the varying precision (COM vertical velocity: $p = 0.004$; hip angular velocity: $p = 0.049$) tasks. A similar interaction was observed for maximum knee angular velocity during the varying duration tasks ($p = 0.034$; Fig. 2). In each of these interactions, velocities increased disproportionately less in older compared to younger participants as lift height, precision demand or task duration increased. Similar trends were observed for all three velocity measures during transitions back up to standing for each task (Table 3).

In addition to moving slower, older participants adopted object-retrieval postures that were more upright than those used by younger participants. These postures were characterized by less flexion in the knees and hips, which resulted in a higher vertical COM position (Fig. 3). Specifically, whole body COM was higher in the older cohort by 10% during the varying lift height tasks (0.79 (0.09) m versus 0.72 (0.12) m; $p = 0.013$), 14% during the varying precision tasks (0.69 (0.07) m versus 0.61 (0.09) m; $p = 0.015$), and 20% during the varying duration tasks (0.64 (0.09) m versus 0.53 (0.10) m; $p = 0.019$). These comparatively higher COM positions in the older cohort resulted from: 9% less hip and 46% less knee flexion during the varying lift height tasks; 5% less hip and 39% less knee flexion during the varying precision tasks; and 6% less hip and 41% less knee flexion during the varying duration tasks (Fig. 3). Significant ordinal interaction effects were observed during the varying lift height tasks for COM height ($p = 0.046$), and during the varying precision tasks for maximum knee flexion angle ($p = 0.028$). The nature of these interactions was similar to that observed in the velocity measures, with older participants lowering their whole body COM to a lesser extent than younger participants in response to decreasing lift heights, and not increasing their maximum knee flexion angles as much as younger participants when faced with increased precision demands (Fig. 3).

Table 2
Mean (SD) and *t*-test results for isometric strength (normalized to total body mass) and passive ROM measures.

		Younger ($n = 12$)	Older ($n = 12$)	*t*-Value	*p*-Value
Strength (Nm/kg)	Knee extensor	2.28 (0.75)	1.58 (0.67)	2.393	0.026[a]
	Knee flexor	1.05 (0.37)	0.72 (0.24)	2.616	0.016[a]
ROM (degrees)	Hip flexion	97.5 (18.8)	88.4 (14.8)	1.314	0.202
	Hip extension	54.4 (22.7)	39.4 (7.7)	2.164	0.042[a]
	Knee flexion	144.5 (11.5)	128.7 (15.3)	2.863	0.009[a]
	Knee extension	7.6 (5.7)	4.3 (1.8)	1.873	0.074

[a] Indicates significant age-effect ($p < 0.05$).

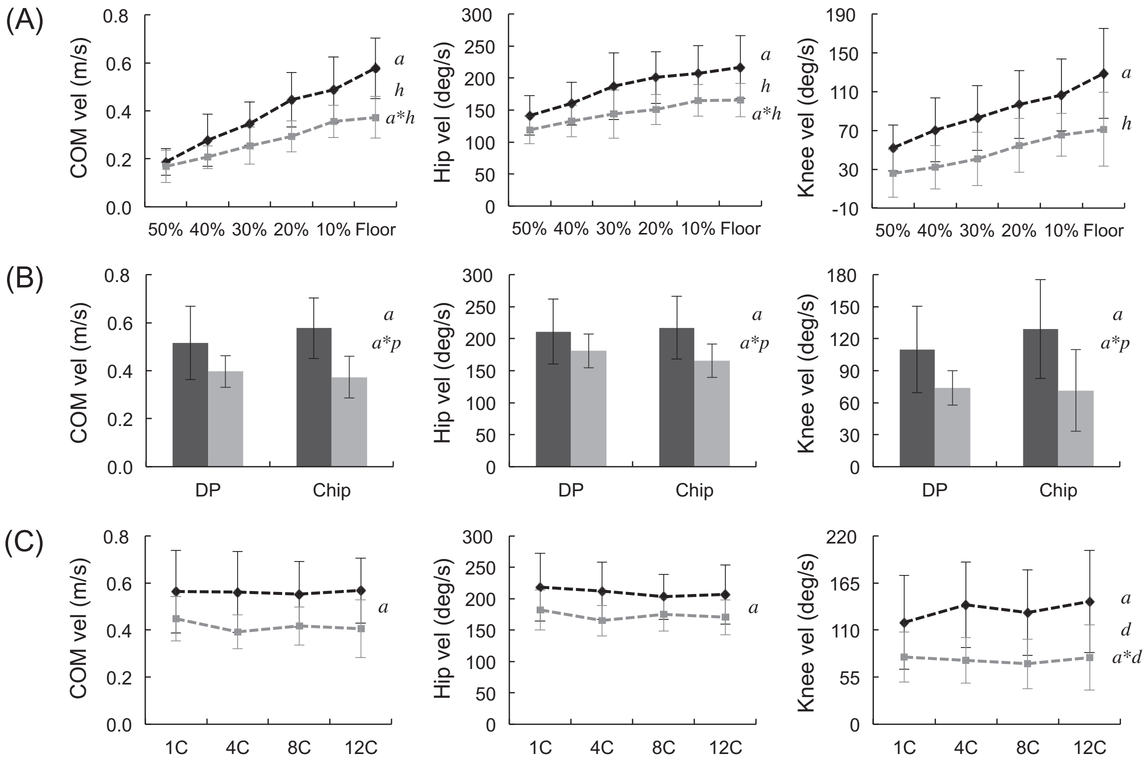

Fig. 2. Speed of movement during descent: maximum COM vertical and hip and knee angular velocities during transitions down from standing to postures used for the (A) varying lift height, (B) varying precision, and (C) varying duration tasks. Black represents young participants; grey represents older participants. Error bars represent +/− one standard deviation from the mean. Significant age (*a*), lift height (*h*), precision (*p*), duration (*d*), and interaction (*a*h*, *a*p*, *a*d*) effects are depicted in the figure.

Table 3
Age group means (SD) for maximum upward vertical velocity of COM, and maximum hip and knee joint angular velocities during the transition-up phase of all tasks. Negative values represent extension of the knee and hip. *p*-values from the repeated measures ANOVA tests are shown for each velocity measure.

Group means				*p*-Value		
Task	Max velocity	Younger	Older	Age	Condition	Interaction
Lift height	COM vert (m/s)	0.42 (0.18)	0.32 (0.12)	0.002[a]	<0.001[b]	0.015[ab]
	Hip vel (°/s)	−174.3 (40.2)	−144.1 (32.4)	0.008[a]	<0.001[b]	0.639
	Knee vel (°/s)	−91.9 (48.6)	−48.1 (29.9)	<0.001[a]	<0.001[b]	0.024[ab]
Precision	COM vert (m/s)	0.59 (0.13)	0.44 (0.07)	0.001[a]	0.002[b]	0.123
	Hip vel (°/s)	−201.8 (35.5)	−167.3 (25.0)	0.008[a]	0.773	0.323
	Knee vel (°/s)	−131.7 (48.1)	−69.8 (25.6)	<0.001[a]	0.020[b]	0.058
Duration	COM vert (m/s)	0.58 (0.15)	0.42 (0.11)	0.004[a]	0.865	0.547
	Hip vel (°/s)	−185.9 (38.0)	−157.9 (23.0)	0.014[a]	0.048[b]	0.953
	Knee vel (°/s)	−139.3 (54.3)	−69.0 (34.9)	0.001[a]	0.116	0.752

[a] Significant age effect ($p < 0.05$).
[b] Significant task condition (lift height, precision, or duration) effect ($p < 0.05$).
[ab] Significant interaction (age*condition) effect ($p < 0.05$).

Calcaneus marker positions indicated that, during the varying duration tasks, older participants were 75% less likely than young participants to employ a forefoot BOS, high knee flexion crouching posture, as they raised their heels above the support surface to initiate this posture in only 13% of the trials, compared to 50% for younger participants (Fig. 4; $p < 0.001$). Further, longer tasks seemed to encourage the crouching posture to a greater extent in younger compared to older participants, as during the 8 and 12 chip (longer) tasks, younger participants crouched in 16 of the 24 trials (67%), whereas older participants did so in only 4 out of 24 (17%) of the trials ($p = 0.001$).

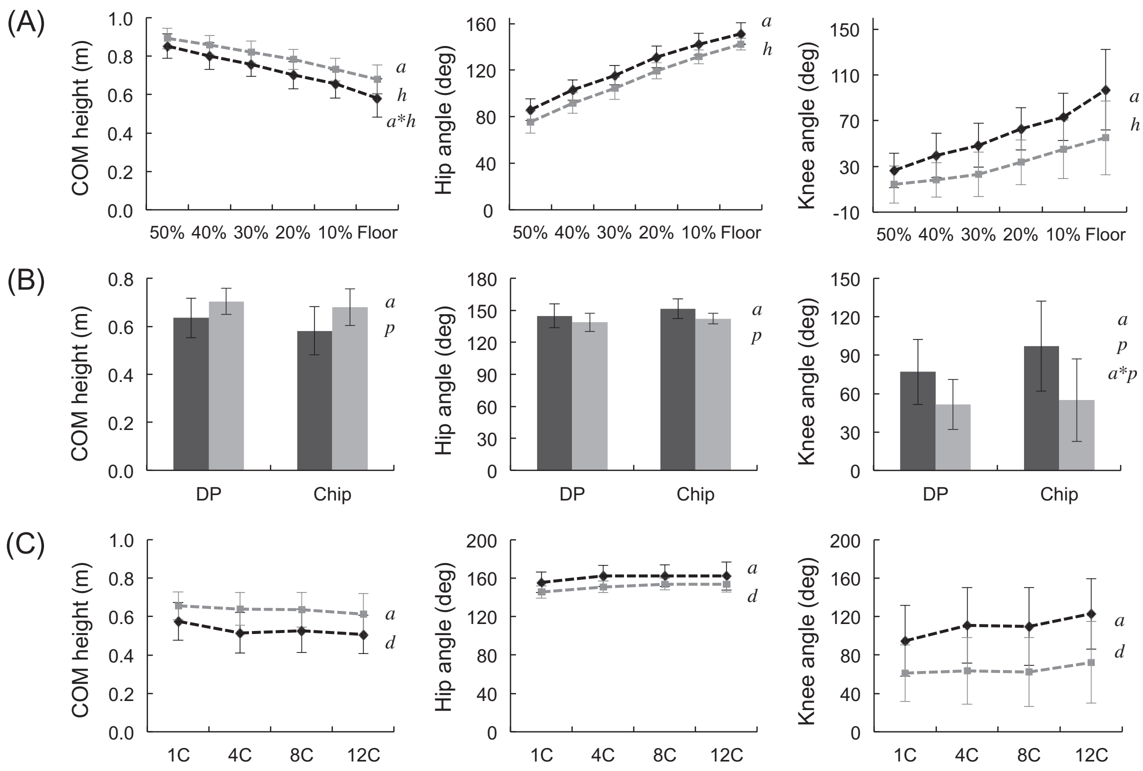

Fig. 3. Postural descriptors: COM height and hip and knee flexion angles at the moment of object retrieval during the (A) varying lift height, (B) varying precision, and (C) varying duration tasks. Black represents young participants; grey represents older participants. Error bars represent +/− one standard deviation from the mean. Significant age (*a*), lift height (*h*), precision (*p*), duration (*d*), and interaction (*a*h*, *a*p*) effects are depicted in the figure.

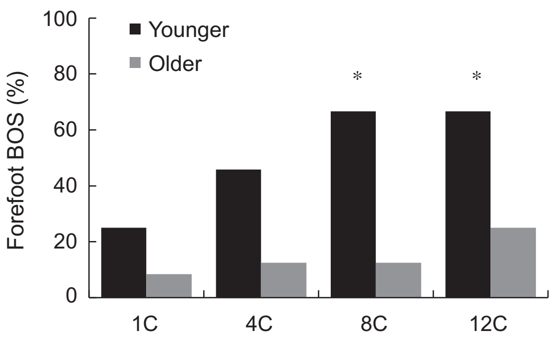

Fig. 4. Comparison of foot posture type between younger (black) and older (grey) participants during the varying duration tasks. Data are displayed as proportions of participants in each age cohort ($n = 12$ for both groups) using a heels-up, forefoot BOS crouching posture. Significant age-related differences at each duration interval (i.e., number of chips) are denoted by '∗'.

3.2. Balance control

In all of the tasks, older adults exhibited faster and more frequent COP trajectory adjustments compared to younger participants (Fig. 5). Specifically, during the varying precision tasks, older participants (1.89 (0.77) cross/s) had a 47% higher *CrossRate* than younger participants (1.29 (0.43) cross/s; $p = 0.022$). The varying lift height and varying duration tasks yielded

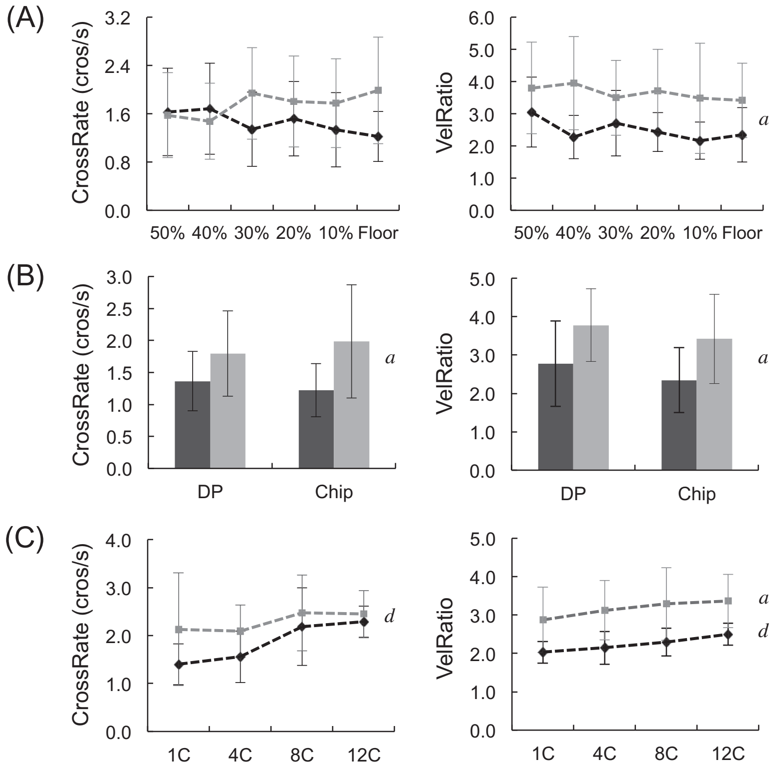

Fig. 5. Balance control measures: *CrossRate* (the rate at which the COP crosses over the COM) and *VelRatio* (ratio of mean COP to COM velocity) during the (A) varying lift height, (B) varying precision, and (C) varying duration tasks. Black represents young participants; grey represents older participants. Error bars represent +/− one standard deviation from the mean. Significant age (*a*) and duration (*d*) effects are depicted in the figure.

similar trends, although these differences in *CrossRate* (21% and 19% higher in older participants, respectively) were not statistically significant. Differences in *VelRatio* were significant in all three tasks, with older participants displaying values that were higher by: 46% during the varying lift height tasks (3.64 (0.21) versus 2.50 (0.22); $p = 0.003$), 40% during the varying precision tasks (3.60 (0.15) versus 2.56 (0.19); $p = 0.024$), and 41% during the varying duration tasks (3.16 (0.11) versus 2.24 (0.07); $p = 0.002$). Increasing task difficulty significantly affected these COP and COM trajectory measures only during the varying duration tasks, with *CrossRate* and *VelRatio* increasing in both age groups as tasks became longer (Fig. 5). Specifically, compared to the 1 chip condition, *CrossRate* increased by 33% (1 chip: 1.79 (0.93); 12 chips: 2.37 (0.41); $p_{\mathrm{ANOVA}} = 0.016$) and *VelRatio* increased by 21% (1 chip: 2.43 (0.74); 12 chips: 2.93 (0.68); $p_{\mathrm{ANOVA}} = 0.004$) during the longer, 12 chip condition. No interactions were observed in either measure for any of the tasks.

4. Discussion

This study presents original data describing age-related differences in sagittal plane kinematics and balance control during SC tasks. Our results support existing works (Kuo et al., 2011; Mourey, Grishin, D'Athis, Pozzo, & Stapley, 2000) in demonstrating that, when moving into and out of SC postures, older participants exhibited lower velocities than their younger counterparts. Older adults also employed postures that were generally more upright – characterized by higher vertical COM positions and comparatively less knee and hip flexion (Kuo et al., 2011). In addition to moving slower and not getting as low to the floor, older participants tended to exhibit faster and more frequent COP trajectory adjustments throughout the tasks. An interesting exploratory finding was that, for longer-duration tasks in particular, older participants were less likely to adopt a high knee flexion, crouching posture, which seemed preferred by younger participants. This posture consists of a reduced BOS, wherein the heels are raised and only the forefeet remain in contact with the floor. Older participants tended to prefer a flat-footed, straighter-legged, stooping posture, bending primarily at the waist to complete the tasks. Comparatively lower knee extensor strength and ROM values in older participants likely contributed to these kinematic and COP control differences.

Examining the nature of each age group's response to the changing task demands provides important insights into potential limitations affecting older adults. For example, while participants in both groups responded to lower initial lift heights by correspondingly lowering their whole body COM, the response was markedly subdued in older compared to younger participants (Fig. 3). Similarly, older participants' velocity increases were disproportionately smaller than those of younger adults during transitions down to or back up from postures used at progressively lower lift heights (Fig. 2). These diverging responses may reflect a physical limitation-based reluctance by older adults to (1) lower their COM into a position from which they might have difficulty standing back up, and (2) move at velocities that require levels of strength and coordination near or beyond their capacity. Indeed, several research groups have demonstrated that older adults may be unable to rise from lowered chair heights because the necessary knee extensor moments exceed what they are capable of producing (Hughes, Myers, & Schenkman, 1996; Rodosky, Andriacchi, & Andersson, 1989). While direct comparisons between those works and the present study cannot be made, our observation that older adults' knee extensor strength was 30% lower than that of younger participants' may, in part, explain why older adults did not progressively lower their pick-up postures to the same extent as their younger counterparts. Knee extensor strength is also known to correlate with linear momentum in older adults during the sit-to-stand (Hughes et al., 1996; Scarborough, Krebs, & Harris, 1999); a movement that, similar to stooping and crouching, requires considerable knee flexion. In addition to strength deficits, which were observed in the current study (Table 2), significantly higher BMI may have also limited older adults from making the same velocity and postural adaptations to the changing task demands that younger participants demonstrated (i.e., moving faster and using higher knee flexion postures for tasks closer to floor level). Indeed, increased BMI has been linked to reduced ROM in the knee and hip (Escalante, Lichtenstein, Dhanda, Cornell, & Hazuda, 1999), impaired mobility (Brown & Flood, 2013), and postural instability (Dutil et al., 2013) in older adults. Potential age-related degradation of sensory function and motor coordination likely further complicated task responses in older participants (Lord, Ward, Williams, & Antsey, 1994; Tinetti, Inouye, Gill, & Doucette, 1995). It is likely that such limitations collectively contributed to older participants' diminished propensity to increase their maximum velocities to the same extent as younger participants during transitions to and from postures used at progressively lower lift heights (Fig. 2).

Similar trends, though not as pronounced, were observed during the varying precision tasks. During these tasks, age-related postural differences tended to increase when participants retrieved the chip compared to the dustpan (Fig. 3). Since smaller objects such as the chip are more difficult to grasp than larger objects, lower postures with the head and eyes closer to the object are typically preferred to optimize visual control (Berthier, Clifton, Gullapalli, McCall, & Robin, 1996; Bootsma, Marteniuk, MacKenzie, & Zaal, 1994). Younger participants were able to achieve these lower postures, making the grasp task easier, whereas older adults' physical limitations likely precluded them from doing the same (Hughes et al., 1996; Long & Pavalko, 2004). Increasing precision demands also differentially affected maximum velocities (Fig. 2; Table 3). Specifically, maximum downward COM velocity tended to increase in younger participants – but decrease in older participants – as precision demands increased from the dustpan to the chip condition (Fig. 2). Similar interactions were observed in the hip and knee joint angular velocities (Fig. 2). It is possible that the increased precision demand of the chip task prompted a shift in older participants from feedforward to feedback control, which consequently slowed them down. Indeed, increased processing demands associated with feedback control (i.e., the continual adjustment of hand trajectory based on sensory information) are known to result in reduced velocities and longer movement times during reach-to-grasp tasks (Berthier et al., 1996; Seidler, Noll, & Thiers, 2004). Younger participants may have been less affected by the increased precision demands, increasing their downward velocity to match the increased movement amplitude of the chip task (Duarte & Freitas, 2005; Hernandez et al., 2012).

Perhaps the most significant result from this study was that, when faced with progressively longer tasks (i.e., more chips to retrieve), older participants tended to avoid the high knee flexion, crouching postures that were commonly used by younger participants. Instead, older adults favoured a straighter-legged, stooping posture to complete the tasks (Fig. 4). The crouching posture employed by younger participants was likely preferred for longer tasks because, with the buttock effectively resting on the calf region, the knee extensor muscles can relax (Dionisio, Almeida, Duarte, & Hirata, 2008; Gallagher, Pollard, & Porter, 2011). However, the transition to and from this posture was likely more difficult, as it requires significantly higher knee extensor moments than would be required for a stoop (Burgess-Limerick, 2003; Giat & Pike, 1992). These strength demands may have discouraged older participants from crouching. Similar results were demonstrated by Hernandez et al. (2013) during a floor-level forward reach task, in which older women – who had comparatively lower knee extensor strength than younger women in the study – exhibited 22% shorter maximum reach distances despite self-selecting 50% larger base of support areas. Our results complement this data by demonstrating that older adults tend to avoid large-amplitude body movements and reduced BOS conditions. Interestingly, the stooping posture preferred by older adults – which involves bending from the waist to complete the tasks – leaves the head and neck in a near-inverted position. Moreover, several groups have reported postural stability impairments with the head and neck in such orientations due to potential challenges associated with integrating sensory inputs from the vestibular system and muscle stretch receptors (Buckley, Anand, Scally, & Elliot, 2005).

Throughout all of the tasks, *CrossRate* (the rate at which the COP crossed over the COM) and *VelRatio* (the ratio of COP to COM mean velocities) tended to be higher in older compared to younger participants (Fig. 5). These results indicate that, despite moving slower, the COP adjustments aimed at controlling COM position made by older adults were faster and more frequent than those made by their younger counterparts. A similar phenomenon has been demonstrated in previous works, whereby older adults utilized nearly twice as many COP sub-movements despite moving 27% slower than younger participants during targeted COP movements (Hernandez et al., 2012). As COP movements typically represent muscle activity aimed at controlling the COM, these results may be due to older adults performing tasks at or near their physical capacity, or reflect a less efficient attempt at closely monitoring their balance (Kuo et al., 2011; Madhavan et al., 2009).

This study involved several limitations. First, while participants were encouraged to perform the tasks naturally, they were not allowed to step off the force platform. This spatial constraint prevented participants from using postures such as kneeling, lunging, or wide-base squatting. Despite these constraints, 21 out of 24 participants indicated they would perform SC tasks in their daily lives exactly as they did in the experiment. Second, movement analyses were restricted to the sagittal plane. Kinematic asymmetries and postural instabilities can occur in the lateral direction as a consequence of sagittal plane movements (Kuo et al., 2011; Singer, Prentice, & McIlroy, 2012). However, as movements required to complete SC tasks occur primarily in the sagittal plane, it was considered most relevant for assessing age-related differences in movement strategies. Third, participants were not matched anthropometrically between age-cohorts, as older participants exhibited significantly higher BMI than younger participants (Table 1). Higher BMI likely affected differences observed in passive ROM (Escalante et al., 1999), making it difficult for older participants to adapt to changing task demands in the same manner demonstrated by younger participants. Nevertheless, it is important to recognize that this difference in BMI is consistent with population-based data (Statistics Canada, 2013), which supports the external validity of our results with regards to BMI. Finally, the older adults in this study were generally healthy individuals capable of performing SC tasks without apparent difficulty. In order to truly evaluate mechanisms underlying SC difficulty or inability in older adults, a study population that better represents the 24% of older adults with SC difficulty is required (Hernandez et al., 2010; Taylor et al., 1997). Nevertheless, investigating the manner in which healthy aging affects these tasks is an important first step and provides valuable insight into the progression of age-related SC performance decline.

The results of this study provide baseline data that may be used to guide interventions aimed at improving functional SC ability in older individuals. Although still able to perform the tasks, older participants in this study displayed significant decreases in movement speed, postural adaptations, and decreases in balance control efficiency compared to younger participants. Physical factors such as reduced lower limb strength and ROM likely contributed to these performance differences, and may be appropriate areas for interventions to target. Hernandez et al. (2010) reported similar findings and suggested that programs aimed at addressing deficits in older adults' SC task performance should focus on building strength in the distal leg musculature. Such targeted interventions may be most effective if incorporated into comprehensive fall-reduction approaches that include balance and coordination activities, active ROM exercises, variations of Tai Chi movements, functional strength training, and aerobic exercises (Barnett, Smith, Lord, Williams, & Baumand, 2003; Hernandez et al., 2010; Li et al., 2005). Further, as individuals with SC difficulty share many characteristics (e.g., ROM limitations and lower extremity strength) with those who have a history of falls (Lord et al., 1994), they may benefit from such interventions by simultaneously improving SC performance and reducing fall risk.

5. Conclusion

This study adds to the existing literature by describing age-related kinematic and COM control differences during natural SC task performance. Our results demonstrate that older adults adapted their movement and control strategies to a lesser extent than younger adults in response to the changing demands of various SC tasks. Of particular interest is the finding that older adults tended to avoid high knee flexion, crouching postures; likely in part because of their diminished knee extensor strength. Future work should focus on investigating causal relationships between physiological and functional traits (i.e., strength, ROM, functional reach) and SC ability. Such knowledge will be essential to devising interventions aimed at improving SC performance and curtailing functional decline in the aging population.

Conflict of interest disclosure

None of the authors have any conflicts of interest related to the materials or details presented in this document. No persons other than the authors had any input into the study design, data analysis, or manuscript development.

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