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Upper Limb Contributions to Frontal Plane Balance Control in Rollator-Assisted Walking

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While assisting with balance is a primary reason for rollator use, few studies have examined how the upper limbs are used for balance. This study examines upper limb contributions to balance control during rollator-assisted walking. We hypothesized that there would be an increased upper limb contribution, measured by mean vertical loading (F_z) and variation in frontal plane center-of-pressure (COP_{high}), when walking balance is challenged/impaired. Experiment 1 compared straight-line and beam-walking in young adults ($n = 11$). As hypothesized, F_z and COP_{high} increased in beam-walking compared to baseline (mean F_z: 13.7 vs. 9.1% body weight (BW), $p < 0.001$, RMS COP_{high}: 1.35 vs. 1.07 cm, $p < 0.001$). Experiment 2 compared older adults who regularly use rollators (RU, $n = 10$) to older adult controls (CTL, $n = 10$). The predicted higher upper limb contribution in the RU group was not supported. However, when individuals were grouped by balance impairment, those with the lowest Berg Balance scores (< 45) demonstrated greater speed-adjusted COP_{high} than those with higher scores ($p = 0.013$). Furthermore, greater COP_{high} and F_z were correlated to greater reduction in step width, supporting the role of upper limb contributions to frontal plane balance. This work will guide studies assessing reliance on rollators by providing a basis for measurement of upper limb balance contributions.

Keywords: assistive devices, high-risk fall patients, older adults

Introduction

The rollator (four-wheeled walker) is a mobility assistive device prescribed to facilitate independent mobility in part by augmenting balance control and reducing the risk of injury due to falls. Although prevalence estimates have not been well-reported, the available numbers indicate a high number of rollator users worldwide. In Sweden, a reported 250,000 people use rollators (Brandt, Iwarsson, & Stahl, 2003) and in the province of Ontario (Canada), an estimated 50,000 new rollators were publicly subsidized between 2001–2006 (Ontario Ministry of Health, personal communication, May 2005). Despite the common use of such assistive aids, studies examining the strategies used by the upper limbs to assist in the control of balance are rare. Tung, Gage, Zabjek, Maki, and McIlroy (2011) found that the upper limbs generated the majority of frontal plane balancing torques compared to the lower limbs in young adults when standing still with rollator. This preference for upper limb control in standing was attributed to the wider base of support (BOS) provided by the rollator frame compared to the width of the feet. Furthermore, increased modulation of phasic center-of-pressure (COP) oscillation was favoured over applying increased vertical load (mean F_z) to generate balancing torques with the upper limbs (Tung et al., 2011). Considering the greater challenge to balance control during walking (i.e., during single-support), the role of the upper limbs in rollator-assisted walking may be more relevant, particularly to individuals with balance impairments. When walking with a rollator, the upper limbs have the advantage of maintaining the BOS width throughout the gait cycle compared to the lower limbs (Bateni & Maki, 2005). An important next step is to determine the characteristics of the upper limb contributions to balance control during walking, particularly when balance control is challenged, as is the case with older adults who are dependent on the use of such mobility aids.

The overall goal of this study was to examine the forces applied to the assistive device and explore the upper limb contributions to balance control during rollator-assisted walking. The specific measures of interest are mean F_z and amplitude of phasic COP. Increased F_z would reflect an increased amount of stabilization torque and high frequency COP (above the frequency associated with the gait cycle) would reflect contributions of reactive balance control. In healthy individuals, a significant source of variability in COP during walking is center-of-mass oscillations is related to cadence (Alwan, Ledoux, Wasson, Sheth, & Huang, 2007). In contrast, a more random, asynchronous loading pattern was observed in a patient using a four-footed walker “to enhance his balance” (Fast et al., 1995, p. 490). In order to disentangle the

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balance control component related to reactive balance control, we separate slower cadence-related oscillations from the faster reactive balance recovery responses in the overall COP signal. Two frequency sub-bands were determined: 1) COP_{low}, a low-frequency band (0.5-1.25 Hz) encompassing the observed range of cadence values (85.8-119.8 steps/min, or 0.71-1.00 Hz), and 2) COP_{high}, a high frequency band (1.25-5 Hz) reflecting upper limb response rise times to unpredictable perturbations during standing (Elger, Wing, & Gilles, 1999).

We hypothesized that upper limb contributions would increase during walking when balance was challenged in young adults or impaired in association to aging. The objective of experiment 1 was to confirm the utility of upper limb kinetic measures as indicators of upper limb contribution to walking balance in young adults. Experiment 2 tested the influence of balance impairment by comparing a group of older adults who relied on rollators for everyday mobility and a control group that walked without assistance. In experiment 1, we predicted that walking under conditions imposing a greater demand on mediolateral balance would be associated with increases in (a) mean vertical load (F_z) and (b) variation in the reactive loading of the rollator, indicated by the root-mean-square (RMS) of high-frequency COP (COP_{high}) compared to a baseline condition. For experiment 2, we hypothesized that the rollator users, who had a greater degree of balance impairment, would demonstrate increased reliance on their upper limbs for walking balance, indicated by increased mean F_z and variation in COP_{high}. The secondary aim of experiment 2 was to assess the impact of upper limb use on walking balance by examining the correlation between upper limb contributions and spatiotemporal gait parameters associated with frontal plane control. Specifically, we hypothesized that individuals with the greatest reliance on upper limbs (i.e., greater mean F_z and COP_{high} variability) with the rollator assistive device would demonstrate the largest increases in gait speed, reduction in step width, and reduction in step width variability compared to individuals with the least reliance on the upper limbs.

Methods

All participants provided informed written consent prior to participating in the study, which was approved by the University of Waterloo (Canada) research ethics board.

Experiment 1: Young Adults

Participants and Tasks

Eleven healthy, young adults (6 female, 5 male, 20–39 years of age) free of (self-reported) gait impairments walked with a rollator (ROL) and unaided (NOROL) in two different tasks: (a) normal walking (NORM) and (b) challenged balance using beam walking (BEAM). For all conditions, participants walked across a 6-m walkway at their preferred speed. In the BEAM task, mediolateral balance was challenged by instructing the participants to walk along a narrow wooden beam (60-cm long x 5-cm wide x 5-cm high) "without stepping off." In ROL trials, participants were not restricted or specifically instructed to use the rollator in any particular way. The rollator handles were adjusted to the height of the radial styloid with arms hanging straight for each participant, according to fitting guidelines (Pierson & Fairchild, 2002). During BEAM trials with the rollator (ROL), the height of the rollator handles were adjusted to accommodate the additional participant height. Trials were conducted in a randomized block design with 6 blocks of 4 trials per block (i.e., ROL/NOROL and NORM/BEAM) for a total of 24 trials.

Measures

Gait speed was measured by the time taken to traverse the middle 5 m of the walkway using optical beams. The number of foot contacts to the floor to recover balance (missteps) during BEAM trials was determined by observing video recordings. Upper limb kinetics were recorded using a custom-built rollator (iWalker) instrumented with four single-axis load cells (SLB-250, Transducer Techniques, Temecula, CA, USA) mounted vertically into each leg of the frame to measure the distribution of F_z (Tung, 2010). In-line strain gage amplifiers (LCV-U5-CAB, Lorenz Messtechnik GmbH, Aldorf, Germany) were mounted underneath the seat. Each load cell was calibrated by placing one wheel of the rollator to isolate a single load cell on top of a forceplate and loading the iWalker using standard weight. Force signals were converted to digital (16 bit, sampling rate 50 Hz) and transmitted wirelessly via Bluetooth radio (BlueSentry-AD, Roving Networks, Los Gatos, CA, USA) to a PDA device (iPaq hx2190, HP Inc., Palo Alto, CA, USA). Considering the applied vertical loading component was observed to contribute 2.5 times more than the horizontal component in quiet standing (Tung, Gage, Zabjek, Maki, & McIlroy, 2011), the vertical forces were used to indicate overall COP applied to the rollator frame in the current study. Load cell signals (acquired at 50 Hz) were low-pass filtered (2nd order Butterworth; 10 Hz) and resolved into an estimate of mediolateral COP (COP_{raw}) using the following relation:

$$COP_{raw} = \frac{D_{Front}\,(F_{FrontLeft} - F_{FrontRight}) + D_{Rear}\,(F_{RearLeft} - F_{RearRight})}{F_{FrontLeft} + F_{FrontRight} + F_{RearLeft} + F_{RearRight}}$$

where $F_{FrontLeft}$, $F_{FrontRight}$, $F_{RearLeft}$, and $F_{RearRight}$, represent vertical forces from the four load cells and D_{Front} and D_{Rear} are horizontal distances to the midline of the walker (22.3 and 26.6 cm, respectively). Total F_z was calculated as the sum of the four load cell outputs and reported as a percentage of BW.

COP_{high}

Two frequency sub-bands were determined: (a) COP_{low}, a low-frequency band (0.5–1.25 Hz) encompassing the observed range of cadence values (85.8–119.8 steps/min, or 0.71–1.00 Hz) and (b) COP_{high}, a high-frequency band (1.25–5 Hz) reflecting upper limb response rise times to unpredictable perturbations during standing (Elger, Wing, & Gilles, 1999). To compute the contribution of the upper limbs for reactive balance control, the raw COP data was bandpass filtered (10th order Butterworth) using the defined COP_{high} cut-off frequencies. RMS values were used to indicate the amplitude of variation of COP_{high}.

Analysis

Paired *t*-tests were used to assess the task related differences in RMS values of COP_{high} and mean F_z. To assess the impact of upper limb use on walking performance, a two-way repeated measures ANOVA (i.e., within-subject) was conducted to analyze the main effects of rollator (ROL/NOROL) and task (NORM/BEAM) on gait speed with interaction effects. A paired t-test on number of missteps when walking in the BEAM condition was used to confirm the balance benefit of using the rollator (ROL/NOROL). Interaction effects were tested using Tukey's least significant difference procedure. Statistical significance was defined as $p \leq 0.05$ for all tests.

Experiment 2: Older Adults

Participants and tasks

For experiment 2, 20 older adults were recruited. A total of 10 older adults who used a rollator for walking balance RU: 4 males and 6 females; mean age = 89.1 years; Table 1) were recruited from a local retirement residence (Schlegel Villages of Winston Park, Waterloo, Canada) and an additional 10 community-dwelling older adults (CTL: 6 males and 4 females; mean age = 83.1 years, Table 1) who did not use a mobility aid were recruited from the Waterloo Research in Aging Participant Pool (University of Waterloo). Inclusion criteria for the RU group were: use of rollator to perform daily mobility activities and ability to follow two-step commands in English. Potential participants were excluded if they were in palliative care, had uncorrected vision, experienced significant pain in standing or moving for brief periods, had diagnosed pathology which severely affected physical function (past 6 months), or were identified by residence staff as a frequent faller (> 2 falls in 1 month). Participants reporting arthritis affecting the upper limbs (i.e., wrist, fingers, elbow, or shoulder) were included if pain was not experienced when using a rollator for mobility. Balance was assessed using the Berg Balance Score (BBS; Berg, Maki, Williams, Holliday, & Wood-Dauphinee, 1992).

All participants walked with (ROL) and without (NOROL) the iWalker at their preferred speed over a 4-m pressure-sensitive mat (GaitRite, CIR Systems Inc., Sparta, NJ, USA) to measure spatiotemporal gait parameters. Prior to collection participants practiced each task twice to familiarize with the rollator and task. Two trials of each condition were performed, presented in random order, with additional walks to ensure > 15 steps per condition. The handles of the iWalker were adjusted to the height of their regular device (RU group), or to fitting guidelines (CTL group). For safety, spotters walked alongside participants.

Measures

COP_{High} and F_z measures were calculated from data collected from the iWalker as described in experiment 1. Spatiotemporal gait measures included mean gait velocity (cm/s), cadence (steps/min), step width (cm), and step width variability (cm, calculated as standard deviation of step width). Changes in gait speed (dVEL), step width (dSW) and step width variability (dSWV) related to using a rollator were determined by calculating the difference between ROL and NOROL trials (e.g., $dSW = SW_{NOROL} - SW_{ROL}$).

Analysis

Unpaired t-tests were conducted to confirm group differences in balance impairment, indicated by the BBS and to compare ages. Based on preliminary analyses, gait speed was positively correlated to both upper limb COP_{high} (Pearson correlation, $r = 0.44$, $p = 0.050$) and mean F_z ($r = 0.56$, $p = 0.011$) and was used as a covariate in subsequent analyses. To test the hypothesis that upper limb involvement is greater in the RU group compared to CTL, one-way ANCOVAs were performed on upper limb measures (COP_{high}, F_z) with group as the main factor with gait velocity included as a covariate and a *speed* × *group*

Table 1. Older adult participant characteristics by group (rollator users [RU] and older adult controls [CTL]).

RU				CTL			
Sex	Age (years)	Berg score	History	Sex	Age (years)	Berg score	History
M	92	41	ST	M	82	55	
F	86	45	ART↑,OP	M	82	54	
F	85	49	CD, DIA	M	80	56	CD
M	86	44	VIS, KA	F	80	52	OP
F	86	38	ST, BT, ART↓	M	87	56	
F	87	38	VIS, ART↑	M	82	52	ART↓, VER
M	88	42	ART↑, ART↓, ST, CD	F	80	46	ART↑, ART↓, CD, OP, HA, TBI
F	97	38	VIS, HA, OP	M	89	39	ART↑, ART↓, HA, CD, DIA
F	93	42	ART↑, KA	F	86	52	
F	91	42	OP	F	82	56	
4M, 6F	89.1	41.9	*Means*	6M, 4F	83.1	51.4	*Means*
	± 4.0	± 3.5	<u>*SD*</u>		± 3.2	± 6.0	*SD*

Note. ART↓ = arthritis (lower limbs); ART↑= arthritis (upper limbs); BT = brain tumor; CD = cardiac disease; DIA = diabetes mellitus; HA = hip arthroplasty; KA = knee arthroplasty; OP = osteoporosis; VER = vertigo; VIS = low vision; ST = stroke.

interaction effect. Despite the significant group differences in balance capabilities as assessed by the BBS (RU vs. CTL: 41.9 ± 3.5 vs. 51.4 ± 6.0, $p < 0.001$), there was degree of overlap in balance capabilities between groups (RU range: 38–49; CTL range: 39–56) . As a result, we conducted a secondary analysis to group individuals by balance abilities. While recommendations for BBS thresholds to indicate fall risk continues to be debated (Neuls et al., 2011), a score of 45 has been used as a generalized threshold with moderate ability of to predict falls (Berg et al., 1992; Bogle Thorbahn & Newton, 1996). Individuals with BBS scores of 45 and lower were included in the BBS_{low} group ($n = 10$), and the BBS_{high} group comprised of individuals with scores above 45 ($n = 10$). Similar to the primary analysis, a one-way ANCOVA was used to test the effect of group (BBS_{low}/BBS_{high}) with gait speed included as a covariate, and *speed × group interaction* term. To test the secondary hypothesis that increased upper limb involvement would be associated with improved frontal plane walking balance, separate linear regressions were conducted using COP_{high} and F_z as dependent variables and change in gait parameters (dVEL, dSW, dSWV) as the output variable, including gait speed as a covariate. F statistics were used to examine whether the regression coefficients were statistically significant ($p \leq 0.05$).

Results

Experiment 1: Young Adults

Descriptive statistics (*Mean* ± *SD*) of gait speed, RMS COP_{high}, and mean F_z observed in experiment 1 are shown in Table 2. As hypothesized, significant increases in COP_{high} [$t(10) = 5.55$, $p < 0.001$] and mean F_z [$t(10) = 5.39$, $p < 0.001$] were observed when comparing BEAM to NORM. Mean vertical load was 9.12% BW versus 13.70% BW for NORM compared to the challenged BEAM condition. Similarly, COP_{high} significantly increased from 1.07 cm in the NORM condition to 1.35 cm in the BEAM walking condition. While the BEAM task was distinguished by a significant decrease in gait speed compared to baseline [Figure 1, $F(1,31) = 87.27$, $p < 0.001$], no significant effect of ROL on gait speed was observed [Figure 1, $F(1,31) = 0.48$, $p = 0.503$]. The reduction in speed related to the BEAM condition was attenuated when using the rollator, indicated by a significant interaction effect Figure 1 [$F(1,31) = 10.98$, $p = 0.002$]. Missteps were significantly reduced when using the rollator on the beam task [$t(10) = 5.87$, $p < 0.001$] occurring in only 0.4% of trials compared to 27.3% of walks without the rollator on the beam.

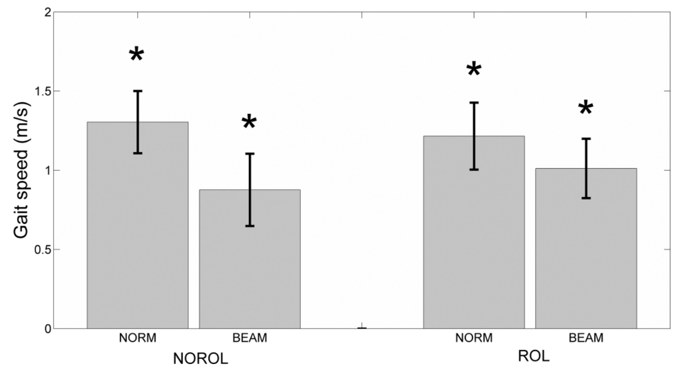

Fig. 1. Experiment 1: *Mean* (± *SD*) gait speed by condition. $^*p < 0.05$.

Experiment 2: Older Adults

Descriptive statistics of the older adult rollator user (RU) and control (CTL) groups are displayed in Table 3. The RU group demonstrated significantly poorer balance, indicated by lower BBS [$t(18) = 4.84$, $p < 0.001$], and was significantly older [Table 3, $t(18) = 3.79$, $p = 0.001$]. The range of observed cadence values across all participants (76.0–129.6 steps/min) corresponds to 0.63–1.08 Hz in the frequency domain and falls within the 0.5–1.25 Hz frequency sub-band used to remove COP oscillations associated with cadence.

The hypothesis predicting increased upper limb contributions in the RU group was not supported by the primary analysis [*Means* F_z: $F(1,17) = 0.23$, $p = 0.639$; RMS $COP_{high:}$ $F(1,17) = 1.15$, $p = 0.300$]. The mean F_z was 12.40 ± 4.62 N and 16.44 ± 6.70 N for the RU and CTL groups, respectively. The RMS COP_{high} was 0.92 ± 0.68 cm and 1.10 ± 0.33 cm for RU and CTL groups, respectively. However, when comparing the groups based on Berg scores there was a significant increase in RMS COP_{high} [$F(1,16) = 6.38$, $p = 0.022$] among those with lower balance scores (BBS_{low} subgroup, 0.88 ± 0.63 cm) compared to the BBS_{hi} subgroup (1.14 ± 0.38 cm) after adjusting for gait speed. However, there was no difference in mean F_z [$F(1,16) = 1.72$, $p = 0.208$] when comparing the BBS_{low} (13.60 ± 4.9% BW) and the BBS_{hi} (14.90 ± 7.17% BW) groups after adjusting for gait speed.

Table 2. Level ground (NORM) and beam (BEAM) walking results from young adults. *Means* ± *SD* are reported.

	No rollator (NOROL)		With rollator (ROL)		P	
	Level ground	Beam walking	Level ground	Beam walking	Task NORM/BEAM	Device NOROL/ROL
Gait speed (m/s)	1.30 ± 0.19	0.88 ± 0.22	1.22 ± 0.19	1.01 ± 0.19	$< 0.001^*$	0.503^{**}
Mean F_Z (% BW)			9.12 ± 7.53	13.70 ± 6.29	$< 0.001^*$	
COP_{high} (cm)			1.07 ± 0.19	1.35 ± 0.22	$< 0.001^*$	
Missteps (% of trials)		27.3%		0.4%		< 0.001

*Significant main effect ($p < 0.05$).
**indicates significant *task × device* interaction ($p < 0.05$).

Table 3. Age, Berg Balance Score (BBS), sex, and baseline walking characteristics grouped by user group (rollator user [RU] and older adult control [CTL]) and balance score (BBS_{lo}/BBS_{high}). *Means* ± *SD* are reported.

	User group			BBS		
	RU ($n = 10$)	CTL ($n = 10$)	p	BBS_{low} ($n = 10$)	BBS_{high} ($n = 10$)	p
Age (years)	89.1 ± 4.0	83.1 ± 3.2	0.001*	84.3 ± 4.1	87.8 ± 4.7	0.096
BBS	41.9 ± 3.5	51.4 ± 6.0	< 0.001*	40.9 ± 2.5	52.8 ± 3.5	< 0.001*
Sex	4 M/6 F	6 M/4 F		5 M/5 F	5 M/5 F	
Baseline gait						
Cadence (steps/min)	98.8 ± 16.4	108.3 ± 11.4		100.7 ± 15.8	106.4 ± 14.5	
Gait speed (cm/s)	55.1 ± 16.4	104.8 ± 27.2		55.0 ± 16.4	104.8 ± 26.2	
Step width (cm)	12.9 ± 2.8	12.2 ± 4.1		14.1 ± 3.8	11.0 ± 2.5	
Step width variability (cm)	2.0 ± 0.9	2.4 ± 0.9		1.8 ± 0.3	2.6 ± 0.9	
Root mean square COP_{high} (cm)	0.92 ± 0.68	1.10 ± 0.33	0.300**	0.88 ± 0.63	1.14 ± 0.38	0.022**
Mean F_z (% BW)	12.40 ± 4.62	16.44 ± 6.70	0.639**	13.60 ± 4.9	14.90 ± 7.17	0.208**

*Significant group difference ($p < 0.05$).
**Analysis with velocity as covariate.

The second hypothesis predicting that individuals exhibiting greater upper limb contributions would demonstrate greatest improvements in gait parameters was partially supported. Greater amplitudes of COP_{high} when using a rollator were significantly correlated to reductions in step width [dSW: $F(1,17) = 5.65$, $p = 0.029$, Figure 2, left) but not step width variability [dSWV: $F(1,17) = 1.0$, $p = 0.331$]. While a there was a trend between COP_{high} and change in gait velocity, it did not reach statistical significance [dVEL: $F(1,17) = 4.35$, $p = 0.0524$]. Greater levels of mean F_z were significantly correlated to decreased step width [dSW: $F(1,17) = 6.87$, $p = 0.018$, Figure 2, right], but not step width variability [dSWV: $F(1,17) = 0.65$, $p = 0.431$) or gait velocity [dVEL: $F(1,17)=0.88$, $p = 0.361$].

Discussion

The overall goal of this study was to characterize the upper limb contributions to the control of balance during rollator assisted walking as reflected by F_z (mean F_z) and amplitude of COP_{high} oscillation. The findings of the current study supported the hypothesis that the upper limbs play a greater role in controlling frontal plane balance during rollator-assisted walking when lower limb balance capabilities are limited or impaired. In experiment 1, healthy young individuals increased the use of the upper limbs, reflected by increases in F_z and COP_{high}, when walking under challenging conditions compared to level ground walking. In experiment 2, older adults with impaired balance (and higher fall risk) rely more on their upper limbs, indicated by significantly higher COP_{high} amplitudes, compared to older adults with low fall risk. Involvement of the upper limbs through the rollator led to improvements in indices of balance control, specifically a significant reduction in missteps off the beam in experiment 1 and greater upper limb involvement correlated to reduced step width in experiment 2. These findings lead to the view that the availability of the upper limbs through a rollator-assistive device may reduce the dependence on the lower limbs for frontal plane balance during walking.

Experiment 1 provided the strongest evidence of the relationship between measures of upper limb use and improved balance. Similar to quiet and laterally-perturbed standing in young adults (Tung et al., 2008, 2011), greater amplitudes of upper limb COP excursion and mean F_z observed in the beam-walking task compared to baseline corresponded to improved balance. While the standing data demonstrated a change in COP excursion, but not in mean F_z, under conditions of increased balance challenge (Tung et al., 2011), the current study demonstrated increases in both mean F_z and COP_{high} excursion in the beam-walking condition compared to normal walking. The gait-related increase in F_z may be attributed to the increased challenge to balance control under walking conditions compared to stationary standing. In contrast, the reliance on upper limb contributions in the balance-impaired group compared to the healthy older adults was not as evident. There are several possible explanations but the most important may be that the task conditions in the young adults explicitly challenged (and limited) ability to control frontal plane balance. In contrast, while frontal plane balance control was challenged in some due to age-related dyscontrol in the older adults, for pragmatic reasons there was no specific task characteristic to limit strategies (e.g., step width, walking speed, or double support time). In fact, slower walking speeds and altered spatiotemporal characteristics between the two groups lead to the view that older adults with impaired balance control reduced the potential ML instability by altering their walking thereby reducing the demand that may be placed on the upper limbs. While we attempted to address this post hoc by using gait speed as a covariate, speed-related effects on upper limb contributions may have been muted by strategy differences as noted previously. Although, it is noteworthy that this was not reflected in the amplitude of the F_z, but rather the high frequency of COP excursion, suggests an increased reliance on reactive control using the upper limbs.

While there are other potential contributing factors, such as familiarity with the use of a walker, the observed correlation between greater upper limb contributions and greater reductions in step width regardless of group supports the link between the measures used (COP_{high} and mean F_z) and frontal plane balance control. There was clear evidence to link increased amplitudes of COP_{high} oscillation to improved frontal plane balance control during walking. In addition to the 23% increase associated with

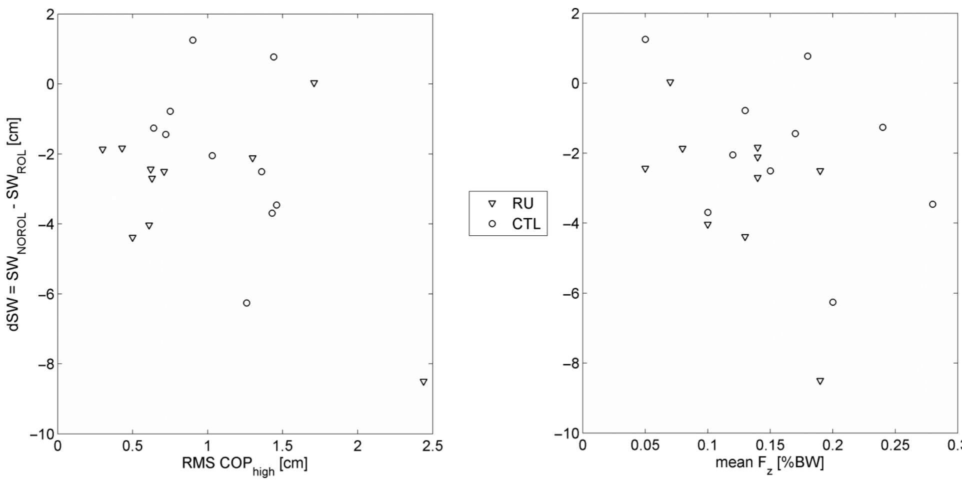

Fig. 2. Scatterplots between upper limb kinetics measures, RMS COP_{high} (left) and mean F_z (right), and change in mean step width (dSW), calculated as the difference between unassisted and rollator-assisted step width. Linear regressions, with gait velocity included as a covariate, demonstrate significant relationships between RMS COP_{high} ($p = 0.029$) and mean F_z ($p = 0.018$) to change in mean step width (dSW). Individual RU (triangles) and CTL participants (circles) are shown.

beam-walking compared to level ground walking in experiment 1, COP_{high} was correlated to reductions in mean step width for older adults in experiment 2. Considering frontal plane balance during unassisted walking is achieved primarily by the placement of the feet relative to the center-of-mass (MacKinnon & Winter, 1993), a reduction in mean step width indicates reduced contributions by the lower limbs to frontal plane control. The observed coupling between reduced lower limb contributions and increased upper limb contributions during assisted walking further supports the use of COP_{high} as an indicator ongoing reactive balance. Future studies examining the temporal coordination between the upper and lower limbs could better inform about reactive and anticipatory balancing strategies employed.

While the increases in mean F_z related to increased balance difficulty in experiment 1 suggest its utility as an indicator of upper limb contributions for balance, vertical load may be confounded by factors other than balance control The strongest evidence supporting the use of mean F_z as an indicator of upper limb balance contributions is from experiment 1, where young adults applied significantly higher vertical loading under challenged walking conditions compared to normal walking. Furthermore, healthy young adults have scaled mean F_z with progressively higher demands on balance control. The lowest levels of mean F_z were reported during quiet standing (2–3% BW; Tung et al., 2011) , the least demanding of balance tasks. During perturbed standing, mean F_z levels rose to 6–9% BW (Tung et al., 2008). In the current study examining normal and challenged walking conditions that pose greater balance demands than standing, young adults applied 9% and 14% BW, respectively. However, the lack of significant differences in experiment 2 in older adults does not support the relationship between mean F_z and increased upper limb contributions to balance. It is noteworthy that, even for those who are routinely dependent on a rollator, the amplitude of vertical load observed in the current study is modest (< 15%) compared to 30–35% reported in progressive supranuclear palsy patient during gait (Fast et al., 1995) or the 20% used to simulate preloading during standing perturbation studies (Bateni, Heung, Zettel, McIlroy, & Maki, 2004) using 4-footed walkers. The moderate loading levels demonstrated in the current study may reflect a compromise between the mechanical advantage afforded by the device and other factors such as fatigue or challenges in maneuvering the rollator. Vertical load may also indicate upper limb use for other purposes, such as reducing dyspnea in chronic obstructive pulmonary disease (Gupta, Brooks, Lacasse, & Goldstein, 2006) or arthritic lower limb pain (de Boer et al., 2009), in addition to balance. Considering these potential confounds, COP amplitudes may provide a more consistent measure of upper limb contributions to balance control than vertical loading.

In light of this examination on the upper limb contributions to walking balance, there were several important limitations of the study that require addressing. First, there may be important contributions associated with additional tactile input when touching a vertical reference (Jeka, 1997), which includes a rollator frame. The lack of means to separate the tactile influences from the overall effects limits the specific examination of mechanical contributions. However, participants in the current study applied substantial forces to their upper limbs and modified these forces according to increased balance demands. While there may be significant contributions to walking balance associated with tactile input alone, the current study highlights the relevance of the mechanical and sensory contributions combined. Second, the lack of available lower limb force data restricted the ability to observe the temporal coupling between the upper and lower limbs. A cycle-by-cycle analysis would complement the link between upper limb involvement and changes to spatiotemporal gait characteristics established in the current study.

The findings from this work may guide future studies by providing an objective measure of upper limb use to assess reliance of rollators for balance during walking. Previous work on assessing gait and balance during rollator use have primarily focused on changes to lower limb control, without corresponding measures of upper limb involvment (Alkjaer, Larsen, Pedersen, Nielsen, &

Simonsen, 2006; Schwenk, Schmidt, Pfisterer, Oster, & Hauer, 2011). The current work provides a foundation to assess upper limb control during rollator-assisted walking and complement existing lower limb measures. For example, evaluating recovery of balance following stroke or traumatic brain injury in assistive device users will benefit from a comprehensive assessment of both upper and lower limb contributions. In addition, measuring the occurrence and intensity of balance recovery reactions during ambulatory recording of rollator use may be a specifically important tool to identify potential fall threats, and the circumstances related to such threats (Tung, 2010).

Overall, this study provides evidence to demonstrate the importance of the upper limbs in maintaining balance in rollator-assisted walking as reflected by their active mechanical involvement and associated changes in gait behavior in the presence of the assistive device. Importantly, this evidence is drawn from healthy and balance-impaired participants, including participants who use rollators for daily mobility activities. By providing a framework to quantify and interpret the mechanical contributions of the upper limbs to complement existing lower limb measures, this work provides a basis to assess reliance on assistive devices for balance during walking.

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