

Predicting balance and quantifying Romberg quotient reference ranges in older adults

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Abstract

Balance control can be quantified with measurements from force plates or wearable accelerometers. The purposes of our study were (1) to assess the explanatory power of accelerometer measures to predict center-of-pressure (CoP) sway-area rate across four standing balance tests, (2) to provide expanded Romberg quotient (RQ) reference ranges for older adults, and (3) to perform an agreement analysis between RQs derived from accelerometer measures with those from CoP sway-area rate. Twenty-six healthy older adults completed four 30-s balance tests standing on rigid and foam surfaces with eyes opened and closed on two occasions. Tests were performed on a force plate (1 variable) while wearing accelerometers (5 variables). The outcomes were assessed with linear mixed-effects models, RQs, and agreement analyses. CoP sway-area rate could be significantly predicted by different combinations of accelerometer variables for each balance condition ($R^2 \geq 0.45$). Despite some accelerometer RQs not being significantly different ($p \geq 0.12$) from corresponding CoP sway-area rate RQs, there was low agreement between these RQs as determined by intraclass correlation coefficients, Bland-Altman plots, and mountain plots. Clinicians with access to wearable accelerometers but not force plates can use our models to estimate CoP sway-area rate for each standardized test of standing balance. The expanded RQ reference ranges provide information about potential sensory impairments that can influence balance control in older adults.

Key words: Standing balance, force plate, accelerometer, agreement analysis

Introduction

Adequate postural control is a prerequisite for independent standing and walking in humans. As we age, however, our ability to maintain balance during upright standing diminishes, resulting in postural instability and its associated sequelae (Lee et al., 2013). This decline in postural control during healthy aging is typically accompanied by reductions in sensory feedback to the central nervous system. One approach to measuring the changes in contributions of sensory systems to balance control is through the use of Romberg's quotient (RQ) (Proske and Gandevia, 2012). Originally developed by the German neurologist M.H. Romberg in the mid-19th century to detect proprioceptive abnormalities (Romberg, 1853), RQ is the ratio of the sway during upright standing between the eyes-open and eyes-closed balance conditions to determine the extent to which vision influences sway.

The diagnostic utility of RQs has been extended to other conditions during upright standing (Sjöman et al., 2018), changes in foot position (Morioka et al., 2000), different standing surfaces (Enache et al., 2017), and to distinguish between individuals with vestibular impairment (Kapoula et al., 2013), diabetic neuropathy (Bonnet and Ray, 2011), or neurodegenerative diseases (Fling et al., 2014) with healthy adults. Critically, the meaningfulness of RQs is limited by the accuracy of the devices used to measure balance as well as the specific measure being compared between balance conditions.

One informative standing balance measure is sway-area rate, which is a compound metric representing the rate of change in the forward-backward and side-to-side displacement of an individual's center of pressure (CoP). It is calculated as the average area encompassed by the CoP location per unit time (Davis et al., 2020; Hufschmidt et al., 1980; Prieto et al., 1996). When compared with other standing balance measures, sway-area rate is less dependent on trial duration and allows for direct comparison among cohorts from different studies. Furthermore, CoP sway area (total area covered during a test of fixed duration) was found to be the most consistent CoP metric associated with falls by a recent systematic review and meta-analysis (Kozinc et al., 2020).

To maintain standing balance, the location of an individual's center of mass (CoM) must remain vertically projected within the boundaries of the base of support (Whittier et al., 2020; Winter, 1995). This is achieved by activating leg muscles to adjust CoP location continuously to accommodate imposed disturbances (Richmond et al., 2021). Although both CoM and CoP trajectories convey information about postural control, the two signals are not directly related (Hortobágyi et al., 2021; Richmond et al., 2021; Winter, 1995). Fortunately, technical advances have made both CoP- and CoM-derived measures more reliable (Hasan et al., 1996; Peterka 2002).

Systems of wearable tri-axial accelerometers with gyroscopes and magnetometers have even been used to calculate RQs in the absence of CoP data obtained from force plates (Fine et al., 2021). Accelerometers placed over the middle of the low back, for example, are often used to estimate CoM location during upright standing (Adlerton et al., 2003; Whitney et al., 2011) and some investigators have reported strong-to-moderate correlations between the same type of standing balance metrics calculated from force plates and accelerometers (Mancini et al., 2012; Najafi et al., 2010). Although force plate and accelerometer measures during standing balance seem to be correlated, it is not clear which accelerometer measures can predict CoP sway-area rate and how this predictive power may change across balance conditions. Although several metrics have been converted into RQs and used to compare the four standard balance conditions, the expected RQ values for commonly used metrics in healthy, older adults have not been specified. Also, it is not known which of the RQs calculated from accelerometers is most closely associated with RQs derived from the clinically relevant CoP sway-area rate metric in older adults.

The purposes of our study on healthy, older adults were threefold: 1) to assess the explanatory power of accelerometer measures to predict CoP sway-area rate across four standing balance tests, 2) to provide expanded RQ reference ranges when standing on rigid and foam surfaces with eyes open and closed, and 3) to perform an agreement analysis between the RQs derived from accelerometer measures and the RQs derived from CoP sway-area rate. We hypothesized that CoM sway-area rate from an accelerometer placed in the middle of the low back would have the greatest predictive power of CoP sway-area rate and greatest RQ agreement with CoP sway-area rate. The outcomes were expected to inform researchers and clinicians about appropriate accelerometer-based metrics and the interpretation of expanded RQ reference ranges for older adults.

Methods

Study Design

Participants ($n = 26$, 70 ± 7 years, range = 60-88 years, 7 men) self-reported no neurological or standing impairments and completed two sessions in which standing balance was evaluated. After reviewing and signing an informed consent document that was approved by the Institutional Review Board at the University of Colorado Boulder, tri-axial Opal™ inertial measuring units (Version 2.0, APDM Inc, Portland, OR; 6 total units) were placed on each participant's sternum, L3/L4 region of the lower back, wrists, and feet.

Participants performed four 30-s balance tests standing barefoot on a balance plate (BTrackS; Balance Tracking Systems, Inc, San Diego, CA) with their feet together and arms crossed over the chest to the contralateral shoulder. Participants stood on a rigid surface with eyes open (REO) and then closed (REC) followed by standing on a foam surface (Balance-pad Airex [50 x 41 x 6 cm], Sins, Switzerland) with eyes open (FEO) and then closed (FEC). In the eyes-open balance conditions, a marker was placed at eye-level approximately 1 m in front of the participant as a focus point.

Each balance trial was explained and demonstrated by the same investigator prior to testing and trials were separated by at least 30 s of rest. Participants were asked not to speak and to stand comfortably for the duration of each trial. The same investigator stood to the side of the participants to provide support when necessary. Three to five weeks later, this protocol was completed a second time as part of a larger study.

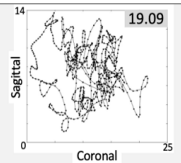
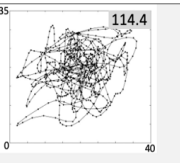
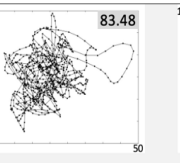
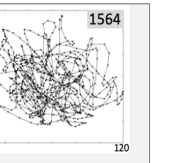
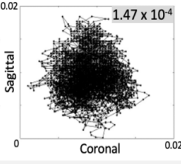
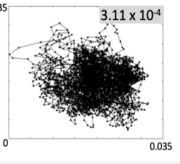
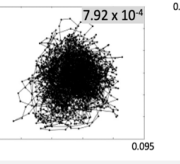
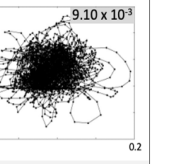
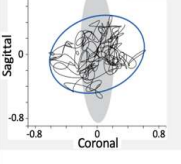
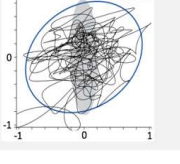
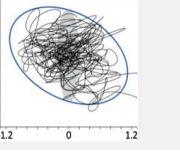
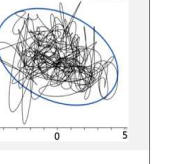
Data Analysis

Six measures of interest were acquired from the two recording instruments. The sole measure calculated from the BTrackS balance plate (sampling frequency of 25 Hz) was CoP sway-area rate. The BTrackS balance plate has been previously validated (Richmond et al., 2018) and CoP sway-area rate RQs were considered the criterion measure for the agreement analyses in our study. CoM sway-area rate was calculated from the accelerometer and gyroscope signals from the inertial measurement unit placed on the low back (sampling frequency of 128 Hz).

The instantaneous x-y displacements for successive time points relative to the mean CoP or CoM location (average of x-y displacements for entire trial) were processed with a custom MATLAB (MathWorks Inc, Natick, MA) algorithm. Sway-area rate for the CoM was derived using the low-back gyroscope signal that was transformed to a Cartesian coordinate system in the transverse plane (Moe-Nilssen, 1998).

The other four measures were provided by APDM's Mobility Lab™ (APDM Inc, <http://apdm.com>) software using all 6 inertial measurement units and included sway area ($\text{m/s}^2 \times \text{m/s}^2$; m^2/s^4), jerk (time derivative of acceleration area; m^2/s^5), mean velocity (m/s), and acceleration root mean square (RMS; m/s^2). These four variables were either derivatives of other measures or were previously found to be correlated between CoP- and accelerometer-derived calculations (Mancini et al., 2012). A description of all outcome variables with example values for each balance condition from a single participant are shown in Table 1.

Table 1. Descriptions of the measurements and exemplary data for a single participant for each balance condition.

Measure	Description	Units	REO	REC	FEO	FEC
CoP Sway-Area Rate	Area enclosed by the center-of-pressure trajectory per unit time	mm ² /s				
CoM Sway-Area Rate	Area enclosed by the center-of-mass trajectory per unit time for lower back IMU	mm ² /s				
APDM Sway Area	Area of an ellipse covering 95% of the sway acceleration in the coronal and sagittal planes	m ² /s ⁴				
APDM Jerk	Time derivative of acceleration	m ² /s ⁵	0.684	4.026	8.272	137.7
APDM Mean Velocity	Sway path length trial duration	m/s	0.174	0.132	0.150	0.512
APDM Root Mean Square	RMS of the sway acceleration in both the coronal and sagittal planes	m/s ²	0.055	0.084	0.100	0.398

Numbers represent the values for each of the measurements (rows) in the four balance conditions (last four columns). Stabilograms in top 3 rows have values specified in top right corners. Grey ellipses in *APDM* Sway Area stabilograms are provided by the *APDM* software and can be ignored. *Sagittal* = forward-backward direction; *Coronal* = side-to-side direction. *CoP* center of pressure; *CoM* center of mass; *REO* rigid surface, eyes open; *REC* rigid surface, eyes closed; *FEO* foam surface, eyes open; *FEC* foam surface, eyes closed.

Statistical Analysis

Linear mixed-effects models were developed to identify outcome measures, as well as self-reported height, that could predict CoP sway-area rate. Height was included in the models as anthropometric measures are known to influence stabilometric parameters (Chiari et al., 2002; Prieto et al., 1996). Due to each participant being tested twice as part of a larger study in which linear mixed-effects models detected no significant performance differences between the two sessions, participants were factored as random effects.

These models were constructed through a combination of variables that were significantly correlated (Pearson product-moment correlation) with CoP sway-area rate and variables that could significantly predict CoP sway-area rate in full models that included all outcome variables.

Models with the lowest Akaike's information criterion values (Akaike, 1974) were selected for each balance condition with partial (conditional) R^2 values for fixed effects also reported (Nakagawa and Schielzeth 2012).

RQs for all balance-condition comparisons and each outcome variable were calculated as the ratio between measures. Because Shapiro-Wilk tests for normality indicated that the data for all variables were nonparametric, the RQs for CoP sway-area rate were compared with those from all other outcome variables via Wilcoxon Signed Rank tests for paired measures. As is customary with agreement analyses, when no statistically significant ($p > 0.05$) differences were detected, intraclass correlation coefficients (ICC; single-rater, absolute agreement, two-way mixed effects model) with 95% confidence intervals are reported (Koo & Li, 2016; Weir, 2005).

The standard error of the measurement (SEM) was calculated as: $SEM = \left(\frac{SD_1 + SD_2}{2} \right) \times \sqrt{1 - ICC}$. Comparisons that were not significantly different were used to create a Bland-Altman plot (Bland & Altman, 1986) and folded empirical cumulative distribution (mountain) plot for two forms of visual representation as recommended for agreement analyses (Scott et al., 2003). Data are reported as mean $\pm$ standard deviation unless stated otherwise. All statistical procedures were performed using R (Version 4.0.3) with significance set to an α level of $p \leq 0.05$.

Results

The results comprised measures of correlations and predictive linear mixed-effects models between accelerometer variables and CoP sway-area rate. RQs were calculated for each balance variable for each balance condition comparison. Agreement analyses between RQs from accelerometer variables and RQs from CoP sway-area rate are reported.

CoP sway-area rate for the REO balance condition was significantly correlated with APDM measures of sway area and jerk, whereas the correlated variables for the REC balance condition were CoM sway-area rate and height (Table 2). CoP sway-area rate for both foam balance conditions (FEO and FEC) was significantly correlated with height and all other outcome variables, excluding APDM mean velocity.

Table 2. Statistically significant ($p \leq 0.05$) Pearson correlation coefficients (r) between CoP sway area rate and accelerometer-derived measures for each balance condition.

Balance condition (CoP Sway-Area Rate, mm ² /s)	CoM Sway-Area Rate (mm ² /s)	APDM Sway Area (m ² /s ⁴)	APDM Jerk (m ² /s ⁵)	APDM Root Mean Square (m/s ²)	Height (m)
REO	–	0.35	0.61	–	–
REC	0.73	–	–	–	0.30
FEO	0.64	0.63	0.83	0.46	0.38
FEC	0.85	0.41	0.68	0.46	0.63

CoP center of pressure; CoM center of mass; REO rigid surface eyes open; REC rigid surface eyes closed; FEO foam surface eyes open; FEC foam surface eyes closed.

The predictive linear mixed-effects models for CoP sway-area rate are reported in Table 3. The predictive power (whole-model R^2) ranged from 0.45 to 0.91 across the four balance conditions, with three conditions reporting high values (0.87-0.91). The relative contributions of each variable to the predictive model are indicated as partial R^2 values in the table cells. The models for the two eyes-closed balance conditions included five variables, whereas the models for the two eyes-open balance conditions included three variables. APDM sway area and jerk were common to all models, whereas APDM mean velocity was not included in any model.

Table 3. Whole-model R^2 and partial (conditional) R^2 values for the linear mixed-effects models that explained statistically significant ($p \leq 0.05$) amounts of the variance in CoP sway-area rate for each balance condition.

Balance condition (Whole-model R^2 predicting CoP Sway-Area Rate; mm ² /s)	CoM Sway-Area Rate (mm ² /s)	APDM Sway Area (m ² /s ⁴)	APDM Jerk (m ² /s ⁵)	APDM Root Mean Square (m/s ²)	Height (m)
REO ($R^2 = 0.45$)	–	0.10	0.36	0.07	–
REC ($R^2 = 0.91$)	0.66	0.45	0.40	0.28	0.23
FEO ($R^2 = 0.91$)	0.22	0.23	0.65	–	–
FEC ($R^2 = 0.87$)	0.68	0.19	0.31	0.25	0.44

CoP center of pressure; CoM center of mass; REO rigid surface eyes open; REC rigid surface eyes closed; FEO foam surface eyes open; FEC foam surface eyes closed.

The expanded RQ reference ranges are shown in Figure 1. Note that an RQ value of 1 indicates that the values for the variable are similar for the two balance conditions being compared. The RQs for the REC-FEO comparison were the most consistent with values close to 1 for all measures. When comparing these two balance conditions (REC and FEO) with REO, the average RQs for CoP sway-area rate were ~3-4. When the FEC balance condition was compared with either REC or FEO, the average RQs for CoP sway-area rate were ~7-9. The average RQs for CoP sway-area rate in the REO-FEC comparison were ~24. As the same six participants were unable to complete the FEC balance condition on both testing sessions, the RQs involving a comparison with FEC have fewer data points and artificially low mean values.

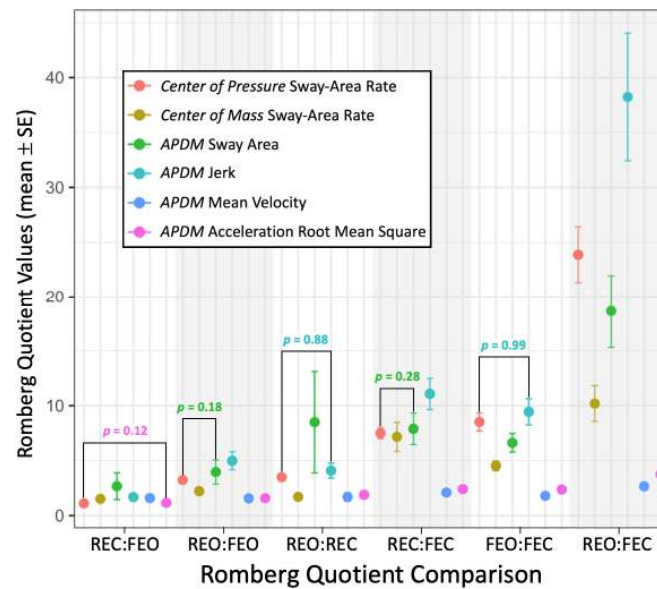


Figure 1. Expanded Romberg Quotient (RQ) reference ranges for healthy older adults derived from 6 balance variables (inset) across 4 balance conditions. RQs correspond to the ratio between the balance conditions specified along the x-axis, which are shown in order of increasing mean values for CoP sway-area rate. Some standard error bars are hidden by the associated mean value point. RQs that were not significantly different between variables are indicated by the black brackets connecting the two variables. Otherwise, the RQs derived from all other variables in each balance condition were significantly different from the corresponding CoP sway-area rate RQ. *REO* rigid surface eyes open; *REC* rigid surface eyes closed; *FEO* foam surface eyes open; *FEC* foam surface eyes closed.

Wilcoxon Signed Rank tests revealed that RQs derived from APDM jerk for the REO-REC and FEO-FEC comparisons and those derived from APDM acceleration RMS for the REC-FEO comparison were not significantly different ($P \geq 0.12$) from the RQs obtained from the corresponding CoP sway-area rate values (Figure 1). Further, RQs derived from APDM sway area for the REO-FEO and REC-FEC comparisons were not significantly different ($p \geq 0.18$) from the corresponding RQs from the CoP sway-area rate values. The absolute agreement between all comparisons was poor ($ICC < 0.50$), except for the RQs of APDM jerk for the FEO-FEC comparison (Table 4).

Table 4. Descriptive statistics for the agreement analyses.

Comparison Measure	Balance-Condition Comparison	CoP Sway-Area Rate RQ	Comparison Measure RQ	Wilcoxon Signed Rank test	Mean Difference & Limits of Agreement	ICC (95% CI)	SE M
<i>Jerk</i>	FEO : FEC	8.52 ± 5.21	9.44 ± 7.10	$p = 0.99$	-1.03 (-11.90, 9.84)	0.59 (0.42, 0.72)	3.94
<i>Jerk</i>	REO : REC	3.50 ± 2.11	4.09 ± 4.79	$p = 0.88$	-0.53 (-9.55, 8.49)	0.24 (0.01, 0.44)	3.01
<i>Acceleration RMS</i>	REC : FEO	1.11 ± 0.73	1.17 ± 0.95	$p = 0.12$	-0.08 (-2.13, 1.96)	0.26 (0.03, 0.46)	0.72
<i>Sway Area</i>	REC : FEC	7.50 ± 3.19	7.89 ± 8.60	$p = 0.28$	-0.43 (-15.38, 14.53)	0.32 (0.10, 0.51)	4.86
<i>Sway Area</i>	REO : FEO	3.24 ± 1.70	3.96 ± 7.81	$p = 0.18$	-0.83 (-15.93, 14.26)	0.11 (-0.13, 0.33)	4.49

CoP center of pressure; *RQ* Romberg quotient; *ICC* intraclass correlation coefficient; *CI* confidence interval; *SEM* standard error of measurement; *RMS* root mean square; *REO* rigid surface, eyes open; *REC* rigid surface, eyes closed; *FEO* foam surface, eyes open; *FEC* foam surface, eyes closed.

The distribution of data in Figure 2A suggests that some variables provide specific RQs that were more consistently similar to the corresponding RQ derived from CoP sway-area rate than other variables. Figure 2B shows that although approximately 80% of the RQ comparisons (Figure 2B data points above the horizontal Percentile Rank line from 0.1-0.9) were within a ~2-point difference from the corresponding RQ for CoP sway-area rate, the remaining 20% diverged considerably as indicated by the wide tails in the Mountain plot.

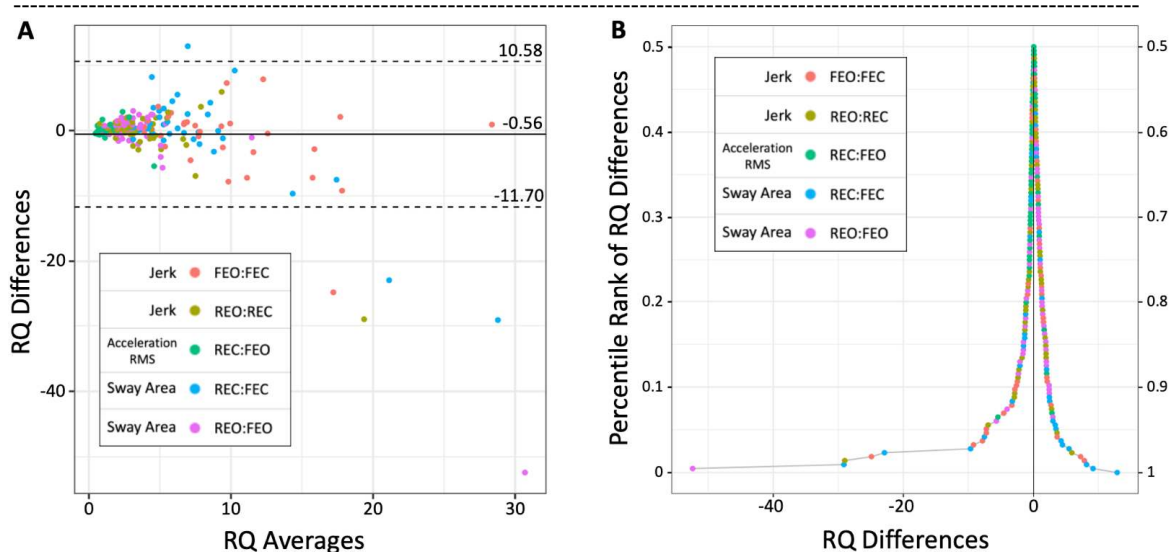


Figure 2. (A) Bland-Altman plot and (B) Mountain plot for the five RQ comparisons. A) mean difference (solid line) and upper and lower limits (dashed lines) of agreement for the values listed in Table 3. B) Interpretation of how closely two measures “agree” can be inferred from the narrowness of the ascending and descending limbs relative to the vertical zero-difference line (50% of data on both sides of the Mountain’s “peak”) as well as how broadly tails of the data spread in each direction. *RQ* Romberg quotient; *REO* rigid surface eyes open; *REC* rigid surface eyes closed; *FEO* foam surface eyes open; *FEC* foam surface eyes closed

Discussion

Our results reveal considerable clinical implications for assessing standing balance, but the details need to be understood prior to application. To meet this need, the main findings are discussed relative to the three purposes of the study.

Prediction of CoP Sway-Area Rate from Accelerometer Measures

One of the main findings of this study was that several accelerometer-based measures could significantly predict CoP sway-area rate in the four standing balance conditions. A clinician lacking access to force plates and the direct acquisition of CoP sway-area rate can still estimate this clinically meaningful metric from the variables included for each model in Table 3. The largest partial R^2 values for CoM sway-area rate in two of the four balance conditions (REC and FEC) partially supports our hypothesis that this variable has the greatest predictive power for CoP sway-area rate.

Partial R^2 values quantify the amount of variance explained by the regression coefficients in a linear model (Stoffel et al., 2021). Therefore, the largest partial R^2 values for both eyes-closed balance conditions (REC and FEC) indicate that the variance in CoP sway-area rate was most explained by CoM sway-area rate in the absence of visual feedback (Table 3). This suggests that vision may provide anticipatory control over CoM movement. Conversely, APDM jerk had the highest partial R^2 values for both eyes-open balance conditions, indicating that a possible strategy by which older adults augment control of CoM movement in the presence of visual feedback is through greater adjustments in the rate of change in sway acceleration (i.e., jerk). The diminished control over CoM movement when vision is removed appears to be exacerbated for taller individuals as height was only predictive for CoP sway-area rate in both eyes-closed balance conditions.

Although others have reported moderate correlations between sway-area rate calculated from both the CoP and accelerometers in the REO balance condition (Mancini et al., 2012), we found that REO was the only balance condition in which CoP sway-area rate and CoM sway-area rate were not significantly correlated (Table 2). Notably, Mancini and colleagues (2012) had participants stand with their feet fixed at 10 cm apart only in REO balance conditions in contrast to our requirement that the feet be touching. Despite many variables being correlated with CoP sway area rate for each balance condition (Table 2), our models demonstrate that correlation does not infer predictive power for CoP sway area rate (Table 3).

One of the unexpected findings was an absence of any statistically significant correlations or predictive power between APDM mean velocity and CoP sway area for any of the balance conditions (Tables 2 & 3). Also, although APDM acceleration RMS had statistically significant predictive power for all balance conditions except REC, the partial R^2 values were relatively low compared with the other variables (Table 3). One explanation could be that both APDM mean velocity and acceleration RMS have more prominent ceiling effects, which is evident from the expanded RQ reference ranges displayed in Figure 1.

Expanded RQ Reference Ranges

Our reporting of expanded RQ reference ranges for the six variables in all six balance condition comparisons indicates that not all balance metrics provide meaningful information in the form of RQs. For example, the average RQs calculated from APDM mean velocity and APDM acceleration RMS were in the

range of ~1–4, even when comparing the easiest (REO) and most difficult (FEC) balance conditions. Thus, the RQs derived from these two variables have low discriminatory power and should not be considered by a clinician when assessing a patient's sensory contributions to the control of standing balance.

RQs derived from the average CoP sway-area rate for each balance-condition comparison provide a baseline for understanding sensory abnormalities in older adults. The comparison of REC and FEO produced an average RQ ~1, indicating that older adults rely somewhat equally on visual and proprioceptive feedback to control standing balance. The similar CoP sway-area rate values between REC and FEO resulted in similar RQs when these two balance conditions were compared with REO (~3–4) and FEC (~7–9). Given that six of our participants could not complete the FEC trial, which relies predominantly on vestibular feedback as vision is removed and proprioception is compromised, these individuals may have had vestibular impairments. Therefore, simple completion of a 30-s FEC trial suggests adequate vestibular function for controlling standing balance.

Adequate function of the proprioceptive and visual systems, conversely, would be reflected by low RQs for the REO-REC and REO-FEO comparisons, respectively. For example, low RQs for the REO-REC comparison suggest minimal visual compensation during standing balance, whereas low RQs for the REO-FEO comparison suggest minimal proprioceptive compensation during standing balance. Further insight into the role of sensory feedback for the control of standing balance by older adults can be gained by supplemental REC-FEC and FEO-FEC comparisons. Based on the average RQs for CoP sway-area rate shown in Figure 1, for example, an individual with an average or lower RQ for the REO-FEO comparison (indicating no overreliance on proprioception) but a higher-than-average RQ for the REC-FEC comparison suggests that the contribution of proprioception to the control of standing balance for that individual may be further compromised by an absence of vision. Critically, such inferences are only possible when evaluating more than one type of RQ comparison. The balance comparisons other than the traditional REO-REC and REO-FEO ones can be used to supplement a clinician's understanding of how an individual weights the inputs from different sensory systems. Therefore, the expanded RQ reference ranges in healthy older adults provide a reference for interpreting interactions between visual, proprioceptive, and vestibular feedback in the control of standing balance.

RQ Agreement Analyses

Our last main finding was that accelerometer-derived RQs generated for five of the six balance-condition comparisons were not statistically different from the corresponding RQs generated from CoP sway-area rate. Of these five, only the FEO-FEC comparison for APDM jerk had moderate agreement with corresponding CoP Sway-area rate RQs as determined by ICC. Interestingly, the other balance comparison in which APDM jerk RQs were not statistically different from CoP sway-area rate RQs was for the REO-REC comparison. Therefore, when the supporting surface remains constant and only visual feedback changes, APDM jerk appears to be the most appropriate substitute for comparing balance performance when CoP sway-area rate is not available.

Conversely, APDM sway area appears to be the most appropriate substitute when comparing balance conditions in which only the supporting surface changes and visual feedback remains constant (REC-FEC and REO-FEO comparisons). APDM jerk and APDM sway area were the only two variables that had significant predictive power for CoP sway-area rate for all four balance conditions, which may indicate why RQs generated from these variables were most consistently similar to the corresponding RQs from CoP sway-area rate.

APDM acceleration RMS was the only variable that did not have significantly different RQs from those for CoP sway-area rate in the REC-FEO comparison. Notably, these two balance conditions, which are both moderately difficult relative to the other two balance conditions, consistently had the closest values among the six balance variables. As a result, RQs calculated between these balance conditions were the lowest for most variables with values commonly close to 1. The ceiling effect for the APDM acceleration RMS values likely caused the associated RQs to be artificially low for all balance-condition comparisons. Thus, the absence of a statistically significant difference between the RQs for APDM acceleration RMS and CoP sway-area rate for the REC-FEO comparison was likely confounded by the ceiling effect for APDM acceleration RMS. Indeed, when considering the ICC values for the RQs between these measures, despite a remarkably low mean difference, the utility of this agreement is questionable.

Our hypothesis that RQs from CoM sway-area rate would most closely agree with those from CoP sway area rate was not supported. The lack of agreement between RQs from these two variables, as indicated by the statistically significant differences in RQ values for all balance comparisons (Figure 1), underscores that the two variables quantify different features of postural stability (Mancini et al., 2012; Winter 1995). Specifically, CoP and CoM have been described as having an inverse relation with acceleration directed from the CoP towards the CoM. For example, the resultant acceleration will be directed backward when the CoP is located anterior to the CoM and forward when the CoP is located posterior to the CoM. This interaction allows the CoP to keep the CoM vertically projected within the base of support, which results in the CoP reaching the boundary of the base of support before the CoM (Richmond et al., 2021). Therefore, despite the similar calculations used to obtain CoP sway-area rate and CoM sway-area rate, the temporal differences between the two likely explains why RQs generated from each variable were significantly different across all balance comparisons.

Some studies have found significantly larger distances in the transverse plane between the CoP and CoM in older adults with a diabetic neuropathy compared with healthy controls (Corriveau et al., 2000). This difference was increased for the REC balance condition compared with the REO balance condition, demonstrating the

utility of REO-REC RQs for detecting sensory abnormalities. Notably, Corriveau and colleagues (2000) had participants stand with their feet pelvis-width apart, which likely caused the increased distances between the CoP and CoM in the anterior-posterior direction compared with the medial-lateral direction.

The information a clinician can glean from accelerometer-derived RQs will depend on the specific variable being compared. To help guide interpretation of RQs from CoP sway-area rate or the agreeing accelerometer measures for specified balance-comparisons, careful consideration of the proximity to the average RQ values in Figure 1 is paramount for identifying sensory abnormalities in older adults. For example, an RQ value that is X points above the mean CoP sway-area rate RQ for FEO-FEC comparison (~9) would be less indicative of impaired sensory feedback than an RQ that is X points greater than the mean CoP sway-area rate RQ for REO-REC comparison (~4). Due to the variability in the agreement between the various RQs and the corresponding RQs derived from CoP sway-area rate, we recommend testing an individual in the balance trials of interest at least twice. This will allow a clinician to determine the reliability of an observation as the basis for a treatment plan.

One major limitation of our study was that six of our participants were unable to complete the FEC balance condition on both visits. In contrast, other studies reported that all older adult participants (n = 19) were able to complete the FEC balance condition for 50 s (Davis et al., 2020). Additionally, the high level of physical activity in the regional population from which our participants were drawn may make our results less representable of all older adults. Also, although our protocol was based on a standardized set of tests, which requires individuals to stand with the feet together, this position does not mimic normal standing posture and may have augmented sway in the medial-lateral direction.

Conclusion

Several accelerometer-derived measures can significantly predict CoP sway-area rate in older adults when they stand on both rigid and foam surfaces with either eyes open or closed. Although the predictive power of each variable differed across the four balance conditions, our findings indicate that CoP sway-area rate—a clinically meaningful standing balance variable—can be estimated from wearable accelerometers across balance conditions. We also found that the utility of RQ ratios derived from the six variables differed across the four balance conditions, indicating that some balance variables provide greater insight into potential sensory abnormalities than others.

We identified five balance-condition comparisons in which the RQs generated from one of three accelerometer-derived variables were not statistically different from the corresponding RQs generated from CoP sway-area rate. Although this result has practical significance, there is considerable variability in the agreement between these comparisons, suggesting that RQs from these measures are not interchangeable. All the CoM sway-area rate RQs were significantly different from the corresponding CoP sway-area rate RQs, which was not expected and underscores temporal differences in CoP and CoM trajectories during upright standing.

Conflict of interest statement

The authors have no conflict of interest. There was no funding source for this study.

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