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Validation of a Measure of Smoothness of Walking

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Background. Altered biomechanics and/or neural control disrupt the timing of postures and muscle patterns necessary for smooth and regular stepping. Harmonic ratio of trunk accelerations has been proposed as a measure of smoothness of walking. We sought to validate this measure of smoothness by examining the measure in groups expected to differ in smoothness (ie, young and old) and across walking conditions expected to affect smoothness (ie, straight path, curved path, and dual task).

Methods. Thirty young (mean age = 24.4 ± 4.3 years) and 30 older adults (mean age = 77.5 ± 5.1 years) who could ambulate independently participated. We measured linear acceleration of the body along vertical, anterior-posterior, and medial–lateral axes using a triaxial accelerometer firmly attached to the skin over the L3 segment of the lumbar spine during straight path, curved path, and dual task (reciting every other letter of the alphabet) walking.

Results. Older adults had lower harmonic ratio anterior-posterior (HR_{AP}), that is, were less smooth in the direction of motion and walked more slowly than young adults for all walking conditions. Once the analyses were adjusted for walking speed, only HR_{AP} differed between young and old participants for all walking conditions. For the most part, both young and old participants were less smooth for slow pace walking, curved path walking, and dual task walking compared with usual pace straight path walking.

Conclusions. The harmonic ratio, calculated from trunk acceleration, is a valid measure of smoothness of walking, which may be thought of as a measure of the motor control of walking.

Key Words: Gait—Smoothness—Accelerometer.

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SMOOTHNESS is a measure of the rhythmic pattern of acceleration and deceleration of the trunk during walking (1). Smoothness of walking is a function of the integration of the kinematics, kinetics, and the coordination (neural control) of gait. Common problems of gait in older adults, such as abnormalities of posture, postural reflexes, muscle function, and the timing and coordination of posture with the phases of gait, result in a loss of the smooth forward progression of walking (2–4). For example, a lack of hip extension during gait can disrupt the coordination of heel strike of the leading limb with push-off of the trailing limb, a feature of gait that facilitates forward progression of the body, whereas the leading limb transitions from forward to backward movement in the step cycle. A disruption of the coordination of heel strike and push-off can mean prolonged deceleration of the leading limb at heel strike and altered accelerations of the trunk to advance the trailing limb (5,6).

Such age-related changes in gait would most likely be associated with slowing of gait speed; however, a measure of gait speed would not represent the changes in the smoothness of walking. Thus, gait speed measures do not differentiate those who walk slowly but with a "good" pattern of walking from those who walk slowly with marked abnormalities of the mechanics and timing of gait. Measures of gait variability have added to the recognition of age-related abnormalities of gait beyond slow speed alone (7); however, quantitative measures of gait variability focus primarily on the lower extremities and the steps of the individual and limit gait assessment to gait laboratory-like settings, with instrumented walkways typical of research settings. Smoothness of walking, calculated as the harmonic ratio of the trunk acceleration signals collected using a triaxial accelerometer, takes into account the whole body and not just the steps of the lower extremity and can be collected in the clinic and in usual naturalistic settings for walking and is not limited to gait laboratory environments (8,9).

Smoothness of walking has been examined in limited groups of individuals and under very few walking conditions. Older adults, who likely have impaired gait biomechanics and neural control (9,10), individuals with Parkinson's disease (11), and individuals with sensory impairment (12) are less smooth in walking than young adults or individuals without disease. Walking speed is known to affect smoothness of walking. In a sample of young (age range: 22–39 years) healthy adults, walking speed was shown to influence smoothness of walking; self-selected walking speed was the most smooth, whereas slower speeds affected smoothness more than faster speeds (1).

The goal of this work was to further develop the harmonic ratio of trunk acceleration series as a measure of smoothness of walking. Specifically, the purpose was to validate the harmonic ratio by examining groups expected to differ in smoothness (ie, young and old) and across challenging walking conditions expected to affect smoothness (ie, usual pace straight path, slow pace straight path, curved path, and dual task). We hypothesize that older adults will be less smooth than young adults and that slow pace, curved path, and dual task walking will be less smooth than usual pace straight path walking. We also explored the impact of age on smoothness of walking independent of gait speed by examining three groups: young, older adults with gait speed similar to the young adults, and older adults who walk slowly.

Methods

Study Participants

Thirty young and 30 older adults were included in the study. The young adult volunteers were recruited through fliers posted throughout the University. Young participants were between the ages of 18 and 50 and had no diagnosed neuromuscular, cardiopulmonary, or orthopedic conditions that would affect walking. Older participants were identified from a longitudinal study of mobility in older adults. In order to participate in the longitudinal study, the older adults had to be free of (a) neuromuscular disorders that impair movement (including but not limited to Parkinson's disease, stroke, and multiple sclerosis); (b) cancer with active treatment (specifically radiation or chemotherapy) within the past 6 months; (c) nonelective hospitalization for a life-threatening illness or major surgical procedure in the past 6 months; (d) severe pulmonary disease requiring supplemental oxygen or resulting in difficulty breathing at rest or with minimal exertion (such as walking between rooms in their home); and (e) chest pain with activity or a cardiac event, such as heart attack within the past 6 months. All individuals were independent in ambulation without an assistive device or without the assistance of another person. The goal was to enroll older adults with a range of mobility: 10 individuals with poor/fair mobility (defined gait speed <0.80 m/s), 10 individuals with good mobility (defined as gait speed 0.80–1.0 m/s), and 10 individuals with very good mobility (defined as gait speed ≥1.0 m/s).

Measures

The measure of smoothness of walking was based on the methodology previously described by Moe-Nilssen and Menz (1,8,9). Linear accelerations of the body were measured along three axes (vertical, anterior–posterior, and medial–lateral) using a triaxial accelerometer (BIOPAC Systems, Inc., Santa Barbara, CA, USA) firmly attached directly to the skin over the L3 segment of the lumbar spine using a belt around the trunk. A point on the back posterior to the L3 segment was chosen as a surface indicator of the center of mass in upright stance and in walking (8). Trunk accelerations were sampled at 100 Hz.

Testing conditions.—Accelerometer data were collected during straight path walking and during challenging conditions expected to affect smoothness. Each participant completed the following testing conditions in order:

Usual straight path: walking at usual self-selected walking speed in a straight path for 40 feet (12.2 m).

Slow straight path: walking slowly (self-selected) in a straight path for 40 feet (12.2 m).

Straight path while talking: walking in a straight path for 40 feet (12.2 m) while repeating every other letter of the alphabet. Participants were instructed to pay equal attention to walking and talking.

Usual curved path: walking at usual self-selected walking speed around a circle 20 feet (6.1 m) in diameter.

During each condition, participants were timed as they walked over a 4-m distance marked in the path of each condition. Gait speed during the condition was calculated as 4 m/time to walk 4 m.

Data Processing

The harmonic ratio was used as an indication of the smoothness and rhythm of the acceleration patterns. Frequency analyses of the acceleration signals were used to quantify the harmonic ratio. Such measure is based on the assumption that stride frequency can be used as the fundamental frequency of the periodic acceleration signals, that is, acceleration signals are repeated during steady state walking, and the fundamental period of such signals is a multiple of the stride duration. Thus, nonsmooth/irregular walking is characterized by increasing power in signal components that are "out of" phase with stride frequency. In summary, the power ratio of "in-phase" to "out-phase" components of the signal, termed "harmonic ratio," can be used to quantify the smoothness/regularity of the signal. The mathematical derivation of the harmonic ratio measure was based on the detailed description provided by Menz and colleagues (1). The harmonic ratio was derived in the anterior–posterior (HR_{AP}), medial–lateral (HR_{ML}), and vertical (HR_V) directions.

Statistical Analysis

SAS version 9.2 (SAS Institute, Inc., Cary, N C) was used for all statistical analyses. We first fit a mixed linear

Table 1. Smoothness of Walking, *M* (*SD*) of Harmonic Ratio for Young and Old During Various Walking Conditions

	Young	Old	Unadjusted Difference (*SE*)	*p* Value	Adjusted Difference (*SE*)	*p* Value
Harmonic ratio—anterior/posterior						
Usual straight path	4.46 (1.36)	2.68 (1.15)	1.78 (0.36)	<.0001	1.42 (0.37)	.0002
Slow	3.80 (1.86)	2.37 (1.26)	1.43 (0.36)	.0001	1.11 (0.36)	.003
Circle	3.89 (1.66)	2.30 (1.03)	1.59 (0.36)	<.0001	1.16 (0.39)	.003
Dual task	3.63 (1.65)	2.06 (1.00)	1.56 (0.36)	<.0001	1.08 (0.38)	.005
Harmonic ratio—vertical						
Usual straight path	4.50 (1.84)	4.00 (1.40)	0.50 (0.43)	.25	−0.10 (0.44)	.83
Slow	3.79 (1.92)	3.00 (1.66)	0.79 (0.43)	.07	0.36 (0.42)	.39
Circle	4.14 (1.89)	3.36 (1.74)	0.78 (0.43)	.07	0.08 (0.45)	.86
Dual task	3.53 (1.35)	2.89 (1.45)	0.64 (0.43)	.14	−0.06 (0.45)	.89
Harmonic ratio—medial/lateral						
Usual straight path	2.72 (1.21)	2.68 (1.07)	0.04 (0.26)	.88	0.14 (0.28)	.61
Slow	2.31 (1.13)	2.49 (1.20)	−0.18 (0.26)	.50	−0.14 (0.27)	.60
Circle	1.86 (0.77)	2.48 (0.94)	−0.61 (0.26)	.02	−0.46 (0.29)	.11
Dual task	2.11 (0.86)	2.34 (0.92)	−0.23 (0.26)	.39	0.12 (0.29)	.68
Gait speed						
Usual straight path	1.36 (0.17)	1.10 (0.28)	0.26 (0.06)	<.0001	—	—
Slow	0.97 (0.17)	0.80 (0.24)	0.17 (0.06)	.002	—	—
Circle	1.28 (0.15)	0.96 (0.24)	0.32 (0.06)	<.0001	—	—
Dual task	1.16 (0.18)	0.85 (0.26)	0.31 (0.06)	<.0001	—	—

model using the SAS MIXED procedure with each measure of smoothness as the response variable; age group, walking condition, and Age Group × Walking Condition interaction as fixed effects of interest; and a participant random effect to account for same participants performing under multiple conditions and the resulting stochastic nonindependence of observations. Appropriate contrasts were constructed to compare age groups within each walking condition and to make pairwise comparisons between walking conditions within each age group using Fisher's least significant difference. Next, we added gait speed during walking condition as an additional continuous fixed effect covariate to the models to examine whether age group and walking condition differences in harmonic ratio remained significant independent of gait speed. Finally, we examined the Age Group × Walking Speed interaction in all models to determine if the effect of age on smoothness of walking differed at different walking speeds. To ensure the soundness of our statistical approach, we examined the residuals from the mixed models and constructed normal probability plots to determine if they were normally distributed. For all models, the residuals showed approximate normality. Analyses were repeated after stratifying the sample into three groups: young, older adults with gait speed similar to the young (ie, gait speed >1.15 m/s, n = 12), and older adults who walk slowly (gait speed ≤1.15 m/s, n = 18). A gait speed split of 1.15 m/s was selected because it created a group of older adults, which had a usual gait speed that was similar to the young group.

Results

The mean ± standard deviation age of the young participants was 24.4 ± 4.3 years and the old participant was 77.5 ± 5.1 years. The majority of the sample was female (70% in young and 77% in old) and Caucasian (93% both young and old). The young participants' usual self-selected walking speed was faster than the older participants' walking speed (1.36 vs. 1.10 m/s).

Age Group Comparisons

Older adults had lower HR_{AP}, that is, were less smooth in the direction of motion and walked more slowly than young adults for all walking conditions (Table 1). Compared with young, older adults also had lower HR in the vertical direction for all conditions; however, the differences failed to reach statistical significance. Findings for HR in the medial/lateral direction were inconsistent, with young adults demonstrating lower HR, that is, less smooth, than old adults when walking a circle. Once the analyses were adjusted for walking speed, only HR_{AP} differed between young and old for all walking conditions (Table 1). The effect of age on smoothness of walking did not differ at different walking speeds (all Age Group × Walking Speed interactions, p > .20).

Walking Condition Comparisons

For the most part, both young and old participants were less smooth (ie, had lower HR in all directions) for slow pace walking, curved path walking, and dual task walking compared with usual pace straight path walking (Tables 2 and 3). For both young and old participants, dual task walking had the greatest impact on smoothness of walking (ie, greatest decreases in HR from usual pace straight path walking). Curved path walking had the greatest impact on the HR in the medial/lateral direction in young participants. Differences in smoothness of walking between conditions were

Table 2. Paired Comparisons of Smoothness of Walking During Usual Straight Path Walking and Other Walking Conditions in Young

Young						
Usual vs. slow straight path						
	Usual	Slow	Unadjusted difference (*SE*)	*p* value	Adjusted difference* (*SE*)	*p* value
HR anterior/posterior	4.46 (1.36)	3.80 (1.86)	0.66 (0.24)	.006	0.07 (0.30)	.81
HR vertical	4.50 (1.84)	3.79 (1.92)	0.71 (0.30)	.02	–0.13 (0.37)	.74
HR medial/lateral	2.72 (1.21)	2.31 (1.13)	0.42 (0.18)	.02	0.60 (0.23)	.01
Gait speed	1.36 (0.17)	0.97 (0.17)	0.39 (0.03)	<.0001	—	—
Usual straight path vs. circle path						
	Usual	Circle	Unadjusted difference (*SE*)	*p* value	Adjusted difference* (*SE*)	*p* value
HR anterior/posterior	4.46 (1.36)	3.89 (1.66)	0.57 (0.24)	.02	0.44 (0.24)	.06
HR vertical	4.50 (1.84)	4.14 (1.89)	0.35 (0.30)	.23	0.18 (0.30)	.55
HR medial/lateral	2.72 (1.21)	1.86 (0.77)	0.86 (0.18)	<.0001	0.90 (0.18)	<.0001
Gait speed	1.36 (0.17)	1.28 (0.15)	0.08 (0.03)	.004	—	—
Usual straight path vs. dual task						
	Usual	Dual task	Unadjusted difference (*SE*)	*p* value	Adjusted difference* (*SE*)	*p* value
HR anterior/posterior	4.46 (1.36)	3.63 (1.65)	0.83 (0.24)	.0006	0.53 (0.25)	.04
HR vertical	4.50 (1.84)	3.53 (1.35)	0.97 (0.30)	.001	0.54 (0.32)	.09
HR medial/lateral	2.72 (1.21)	2.11(0.86)	0.61 (0.18)	.0009	0.70 (0.20)	.0004
Gait speed	1.36 (0.17)	1.16 (0.18)	0.20 (0.03)	<.0001	—	—

Notes: HR = harmonic ratio.
*Adjusted for gait speed.

primarily explained by differences in walking speed except for smoothness of walking in the medial/lateral direction for young participants. Compared with usual straight path walking, young participants were less smooth in the medial/lateral direction for slow, curved path, and dual task walking even after adjusting for gait speed (Table 2).

Three Group Comparisons

The young and fast old groups demonstrated similar gait speed during the usual condition (Table 4); however, the young group walked more smoothly than the fast old group during usual, circle, and dual task conditions (Figure 1). Even though the young and fast old groups had similar gait speeds during usual walking, the fast old group walked significantly more slowly than the young group during the circle and dual task conditions (Table 4). The young group walked faster and more smoothly than the slow old group for all conditions (Table 4 and Figure 1). The fast old group walked faster than the slow old group during all conditions (Table 4), but they demonstrated similar values for smoothness of walking during all conditions.

Discussion

The harmonic ratio of the trunk acceleration series is a valid measure of smoothness of walking. Smoothness of walking differed between young and older adults, specifically

Table 3. Paired Comparisons of Smoothness of Walking During Usual Straight Path Walking and Other Walking Conditions in Older Adults

Older Adults						
Usual vs. slow straight path						
	Usual	Slow	Unadjusted difference (*SE*)	*p* value	Adjusted difference* (*SE*)	*p* value
HR anterior/posterior	2.68 (1.15)	2.37 (1.26)	0.31 (0.24)	.21	–0.24 (0.28)	.41
HR vertical	4.00 (1.40)	3.00 (1.66)	1.00 (0.30)	.001	0.33 (0.35)	.35
HR medial/lateral	2.68 (1.07)	2.49 (1.20)	0.20 (0.18)	.29	0.31 (0.22)	.15
Gait speed	1.10 (0.28)	0.80 (0.24)	0.30 (0.03)	<.0001	—	—
Usual straight path vs. circle path						
	Usual	Circle	Unadjusted difference (*SE*)	*p* value	Adjusted difference* (*SE*)	*p* value
HR anterior/posterior	2.68 (1.15)	2.30 (1.03)	0.38 (0.24)	.11	0.18 (0.25)	.47
HR vertical	4.00 (1.40)	3.36 (1.74)	0.64 (0.30)	.03	0.36 (0.32)	.26
HR medial/lateral	2.68 (1.07)	2.48 (0.94)	0.21 (0.18)	.26	0.30 (0.19)	.13
Gait speed	1.10 (0.28)	0.96 (0.24)	0.14 (0.03)	<.0001	—	—
Usual straight path vs. dual task						
	Usual	Dual task	Unadjusted difference (*SE*)	*p* value	Adjusted difference* (*SE*)	*p* value
HR anterior/posterior	2.68 (1.15)	2.06 (1.00)	0.61 (0.24)	.01	0.19 (0.27)	.49
HR vertical	4.00 (1.40)	2.89 (1.45)	1.11 (0.30)	.0003	0.58 (0.34)	.09
HR medial/lateral	2.68 (1.07)	2.34 (0.92)	0.34 (0.18)	.06	0.44 (0.21)	.04
Gait speed	1.10 (0.28)	0.85 (0.26)	0.25 (0.03)	<.0001	—	—

Notes: HR = harmonic ratio.
*Adjusted for gait speed.

Table 4. Mean (*SD*) Gait Speed for Young, Fast Old (>1.15 m/s), and Slow Old (≤1.15 m/s) During Various Walking Conditions

Condition	Young, (n = 31)	Fast Old, (n = 12)	Slow Old, (n = 18)
Usual straight path	1.36 (0.17)	1.36 (0.18)	0.92 (0.19)*
Slow	0.97 (0.17)	0.96 (0.19)	0.69 (0.20)*
Circle	1.28 (0.15)	1.16 (0.19)†	0.82 (0.16)*
Dual task	1.16 (0.18)	0.99 (0.25)†	0.75 (0.22)*

* *Notes*: Slow old different than young and fast old, $p < .05$.
† Fast old different than young, $p < .05$.

in the anterior/posterior direction and after adjusting for differences in walking speed, and across walking conditions expected to affect the smoothness of walking. Our finding that older adults are "less smooth" in walking than young adults contradicts the findings of Menz and colleagues (13), who found no differences in the smoothness of the acceleration signals (ie, HR) between young and older participants. This discrepant finding may be explained by the fact that the older participants in their study had better mobility (ie, mean gait speed = 1.17 ± 0.16 m/s) than our participants. In the current study, a conscious effort was made to select older adults with a range of walking abilities. The slower mean gait speed and the greater standard deviation (mean gait speed = 1.10 ± 0.28 m/s) indicate that the participants in the current study were more limited in mobility than those studied by Menz and colleagues (13). However, we also compared a subset of older adults with walking speed similar with the young adults (ie, gait speed = 1.36 m/s), we still found a difference in smoothness of walking between the fast older and the young participants.

Within age groups, smoothness of walking differed across conditions, with dual task walking having the biggest impact on smoothness. Of the four walking conditions examined (usual, slow, curved path, and dual task), dual task walking, as we defined it, was the most novel. Everyday walking is likely to involve walking curves and slowing down (17). Though everyday walking is also likely to include walking and talking, it is very unlikely that the talking involves reciting every other letter of the alphabet (our dual-task walking condition). Tasks that are novel or less well

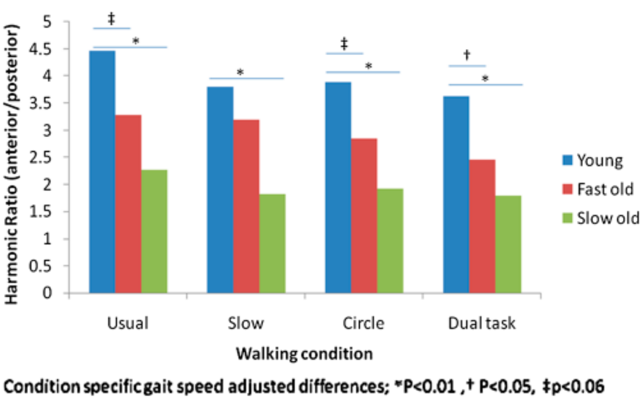

Figure 1. Smoothness of walking for young, fast old (1.15 m/s), and slow old (≤1.15 m/s) during various walking conditions.

learned are challenging to complete and would most likely have the greatest impact on smoothness of walking.

In young participants, walking a curved path had the greatest impact on the HR in the medial/lateral direction. Curved path walking affects the inner and outer leg differently, with shorter stride lengths and greater stance times occur for the inner leg compared with the outer leg. Walking a curve also involves a shift of the body's center of mass to the inner foot (18). These side-to-side differences likely explain the strong impact curved path walking had on the HR in the medial–lateral direction. Curved path walking did not affect the smoothness of walking in older adults as much as it did in young adults. Most likely, the older adults did not demonstrate the side-to-side differences in stride length, stance time, and shifting of the center of mass during curved walking, which are common in young adults. Limiting these side-to-side differences is likely a more cautious way to approach curved path walking.

Walking speed also differed between young and old for all walking conditions. Walking speed has been shown to influence the smoothness of walking, particularly the harmonic ratio (1). Menz examined smoothness of walking at five different self-selected walking speeds. Walking was most smooth (ie, greatest HR) at the self-selected normal speed and was least smooth (ie, lowest HR) at the self-selected slow walking conditions. To determine if the differences in smoothness of walking between young and old were attributed to the differences in walking speed, we adjusted for walking speed in the analyses. The differences in the HR_{AP} between young and old remained after adjusting for differences in walking speed, thus indicating that the differences in smoothness between the young and old participants are independent of the differences in walking speed.

In addition to statistically adjusting for gait speed, we controlled for gait speed by selecting a group of older adults who were similar to the young adults in gait speed (ie, gait speed >1.15 m/s), and two interesting findings emerged. First, even though walking speed was similar (1.36 m/s), the older adults walked less smoothly than the young adults (HR_{AP} older vs. young: 3.28 vs. 4.46, respectively, $p = .01$). The lower HR_{AP} in the older group is most likely capturing the lack of smoothness in walking resulting from abnormalities of the mechanics and coordination of gait that have yet to affect walking speed. Our findings during walking are similar to the work of Morgan and colleagues who showed that when young and older adults perform reaching tasks at the same speed, differences in the quality of the movement exist between the young and old groups (19). Specifically, the older adults demonstrated more submovements, greater hesitancy, and prolonged deceleration compared with the young participants (19). Second, even though usual walking speed was similar for the young and the fast old, the older adults walked more slowly and less smoothly on the more challenging walking conditions (ie, circle path and dual task). Testing older persons only while walking in low challenge situations may fail to distinguish older persons with early mobility difficulty.

The harmonic ratio, calculated from trunk acceleration, is a valid measure of smoothness of walking, which may be thought of as a measure of the motor control of walking. Smoothness of walking could be used in the future to study changes in walking due to specific pathologies and to assess the effects of interventions. Smoothness of walking requires minimal equipment, an accelerometer attached to the trunk, to capture the trunk acceleration series, which is necessary to calculate the HR. The measure has several benefits: (a) It is relatively low cost (compared with a gait laboratory), (b) data collection is not restricted to a laboratory setting, (c) data can be collected over an extended walking distance and over various terrains and conditions, and (d) the accelerometer is relatively small and unobtrusive, so as not to interfere with walking. Further work is needed to determine how smoothness of walking relates to other measures of gait, such as gait variability and dynamic stability, to determine clinically meaningful values of smoothness and to elicit the contributors to and consequences of decreased smoothness.

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