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Age- and speed-related differences in harmonic ratios during walking

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ABSTRACT

Harmonic ratios (HRs), derived from trunk accelerations, measure smoothness of trunk motion during gait; higher ratios indicate greater smoothness. Previous research indicates that young adults optimize HRs at preferred pace, exhibiting reduced HRs at speeds faster and slower than preferred. Recent studies examining HRs and other trunk acceleration measures challenge this finding. The purpose of this study was to examine age-related differences in HRs across a range of self-selected overground walking speeds. Anteroposterior (AP), vertical (VT), and mediolateral (ML) HRs were examined in 13 young adults (ages 20–23), 13 healthy older adults (ages 60–69), and 13 healthy old-old adults (ages 80–86) while walking overground at very slow, slow, preferred, fast, and very fast speeds. Young and older adults exhibited similar HRs in all directions of motion across speeds, while old-old adults exhibited lower AP- and VT-HRs. All groups exhibited reduced HRs at speeds slower than preferred. However, there were no differences in HRs between preferred and faster speeds, with the exception of reduced VT-HRs in the very fast condition for the older groups. The ML-HR was not different between groups, and varied less across speeds. Stride time variability exhibited inverse relations with, and independently contributed to, HRs across speeds; lower stride time variability was associated with greater smoothness of trunk motion. Older groups were not disproportionately affected by walking more slowly and smoothness of trunk motion did not show a clear pattern of optimization at preferred pace for any group.

1. Introduction

Trunk kinematics are sensitive to age-related differences in gait, even in healthy older adults walking at normal speeds [1,2]. One kinematic measure, the harmonic ratio (HR), is derived from anteroposterior (AP), vertical (VT) and mediolateral (ML) trunk accelerations, and quantifies smoothness of trunk motion while walking. Higher HRs correspond to greater smoothness and provide an indication of whole body balance during gait [3,4]. HRs have discriminated between older adults who have and have not fallen [5] and healthy older adults and individuals with Parkinson's disease and peripheral neuropathy [6–8].

Typical AP and VT acceleration patterns have repeatable biphasic patterns that reflect the cyclical movement of the trunk during one stride, thus characterized by a peak frequency at 2 Hz coinciding with step frequency. Mediolateral accelerations, regulated by the stride frequency, exhibit more complex monophasic patterns and are characterized by multiple low amplitude peaks between 1 and 11 Hz. [9,10] In healthy gait, frequency decomposition of AP and VT accelerations per stride yields a dominance of the second harmonic and subsequent even harmonics, as these represent acceleration patterns that are resolved within each stride. The even harmonics represent regular, in-phase accelerations, while the odd harmonics correspond to irregular, out-of-phase accelerations. Conversely, frequency decomposition of ML accelerations yields a dominance of the first harmonic and subsequent odd harmonics, with odd harmonics representing the regular, in-phase accelerations and the even harmonics representing the irregular out-of-phase accelerations stride. [3,11] Thus, HRs provide information regarding an individual's ability to smoothly control trunk motion during gait.

While age-related reductions in HRs have been shown during usual overground walking [1,12], less is known about gait under real world conditions. Home and community ambulation often requires speed changes to successfully adapt to the environment (negotiating furniture, obstacles, and crosswalks) or achieve a goal (answering the door, phone). Examining walking smoothness during the challenges of slow and fast speeds can offer insight into how healthy older adults control speed changes, and reveal conditions where they are most vulnerable.

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Several studies examining the relationship between HRs and walking speed in young adults found an inverted U-shaped response for all directions of motion; HRs were highest at preferred speed, and reduced at speeds faster and slower than preferred [11,13]. Alternatively, others found AP- and VT-HRs were highest at self-selected fast speeds in young men [14], while another study in young and older women walking at preferred and fast speeds found reductions in VT- and ML-HRs, with no change in AP-HR [12]. While these disparate findings may be due to gender, differences in walking speeds and/or methodology, overall the relationships among age, smoothness, and walking speed remain unclear.

To date, no study has compared HRs between young and older adults across a wide range of walking speeds. The primary purpose of this study was to examine smoothness of trunk motion in healthy young adults (YA), healthy 60-year-olds (OA), and healthy 80-year-olds (OOA) during overground walking at self-selected speeds ranging from very slow to very fast. We hypothesized that (1) compared to YAs, OAs would exhibit reduced HRs only at the extreme very fast and very slow speeds, and (2) OOAs would exhibit reduced HRs in general, with disproportionate reductions in HRs at very slow and very fast speeds. Additionally, we examined the contribution of spatiotemporal parameters to HRs across speeds.

2. Methods

2.1. Participants

Thirteen healthy young, old, and old-old adults participated in this study. YAs Young adults were university students. Older adults were recruited from the local community. Reasons for exclusion included neurological diagnoses, history of head trauma, significant heart disease, significant musculoskeletal impairments, or symptoms such as recent fracture or joint replacement, severe chronic pain, peripheral neuropathy, cognitive decline, and use of a walking device. All participants signed an approved written consent form, and were recruited and tested according to institutional review board procedures.

2.2. Instrumentation and procedures

A triaxial accelerometer (Crossbow CXLO2LF3, range ±2 g) mounted to a plastic base plate on a gait belt and secured and aligned with the third lumbar vertebrae [3,15] measured trunk accelerations in AP, VT, and ML directions. The accelerometer was calibrated on a flat surface, and once positioned on the lower trunk, was leveled prior to each trial. Data were sampled at 200 Hz using a portable data logger (Crossbow AD2000 Ready DAQ) worn in a small backpack. Participants, wearing their own comfortable walking shoes walked at 5 speeds based on the following instructions: (1) walk very slowly as if in an art gallery, (2) walk slower than normal, as if there were ample time, (3) walk at preferred, usual speed, (4) walk faster than normal but not maximal speed, and (5) walk as fast as is safe without running. These cues were the same as in previous studies [11,13]. Participants did not fixate on a target, but were told to 'look ahead' and avoid looking around the laboratory. Two markings were made to designate the middle 12.5 m of the walkway for determination of walking speed. Three consecutive trials were performed in each condition. Participants were first asked to walk at their preferred pace followed by slow, very slow, fast and very fast. This order was chosen so that preferred pace would not be contaminated by the other conditions.

2.3. Gait variables

2.3.1. Harmonic ratios

The primary dependent variables were AP-, VT-, and ML-HRs. Full descriptions of HR theory and determination are reported elsewhere [7,13]. The AP- and VT-HRs, calculated by dividing the summed amplitude of the first 20 even harmonics by the summed amplitudes of the first 20 odd harmonics, should be high if the even harmonics dominate the pattern and odd harmonics are small, which is expected in a healthy gait pattern. Conversely, ML accelerations exhibit a monophasic pattern during one stride, thus the first and subsequent odd harmonics are dominant and the HR is calculated from a ratio of the odd harmonics divided by even harmonics [11].

Harmonic analysis was applied to all acceleration data using custom Visual Basic software using National Instruments Measurement Studio™ 6.0 libraries. A low-pass second-order Butterworth filter with a cutoff frequency of 21 Hz was applied to the raw acceleration data prior to stride segmentation. Stride segmentation was determined by identifying local maximum deceleration points in the vertical axis. Maximum deceleration candidate points were determined from negative-going zero-crossings in the first-order derivative of the filtered data. Each stride was classified as consecutive maximum deceleration points (heel strike to heel strike of the same foot). The 'true' heel strike points were then found using a localized search about each point for the maximum deceleration point in the original data. The HR was then determined per stride.

2.3.2. Spatiotemporal variables

Spatiotemporal variables were: average speed (m/s), using a stop watch, the time to walk the middle 12.5 m; stride time (s), number of samples in the acceleration signal between consecutive heel strikes of the same foot × 5 ms/1000 ms; and the coefficient of variation (COV, standard deviation/mean × 100) to quantify the variability of stride time.

2.4. Data reduction and analysis

The first trial was considered practice; values were averaged across trials 2 and 3. Prior to calculation of means, trials were visually inspected to determine if the program correctly selected strides. To avoid acceleration and deceleration effects, the first 2 and last 2 strides were removed from the acceleration data.

All data were checked for normality, and non-significant Kolmogorov–Smirnov statistics and low skewness values were confirmed for each variable. Six separate Group (3) × Condition (5 self-selected speeds) repeated measures ANOVAs were conducted for the AP-, VT- and ML-HRs, walking speed, stride time, and stride time variability. Main effects were interpreted using Bonferroni-corrected pairwise comparisons, interactions were followed up with between group one-way ANOVAs. Alpha level was set at 0.008 (0.05/6). Normalizing the data for leg length did not alter the results, thus the original data are presented. All statistical analyses were performed using PASW 18.

3. Results

3.1. Subject characteristics and self-selected speeds

Subject characteristics and gait speeds for each condition are reported in Table 1. The ANOVA for speed revealed a Group × Condition interaction ($p = 0.004$). Follow up analyses revealed group differences only in the fast ($p = 0.02$) and very fast ($p = 0.012$) conditions, where OOAs walked more slowly than YAs. Within a group, pairwise comparisons revealed that all speed conditions were different from one another, indicating the cues were effective in achieving the desired speed differences.

3.2. Harmonic ratios

Data for all variables for each speed condition are presented in Table 2. The ML-HR differed only by Condition ($p < 0.001$). Pairwise comparisons revealed that ML-HR values in the preferred, fast, and very fast conditions were not different, but were higher than the very slow and slow conditions; the Group effect did not reach significance ($p = 0.047$). The VT-HR analysis revealed a Group × Condition interaction ($p = 0.005$). The OOAs exhibited lower VT-HRs compared to OAs and YAs in the fast condition ($p = 0.005$), and lower values than YAs in the very fast condition ($p = 0.001$). The AP-HR analysis revealed main effects for both Group ($p < 0.001$) and Condition ($p < 0.001$). The OOAs exhibited

Table 1
Means (SD) of subject characteristics and self-selected gait speeds.

	Young adults	Old adults	Old-Old adults
n, # women	13, 9	13, 10	13, 9
Age (yrs)	22.13 (0.9), 20–23	66.34 (2.6), 60–69	82.47 (2.2), 80–86
Leg length (m)	0.90 (0.04)	0.93 (0.06)	0.88 (0.08)
Mass (kg)	69 (12.9)	77.6 (13.4)	67.38 (10)
Gait speed (m/s)			
Very slow	0.56 (0.18)	0.64 (0.17)	0.59 (0.12)
Slow	0.93 (0.19)	1.01 (0.11)	0.96 (0.15)
Preferred	1.33 (0.25)	1.34 (0.13)	1.28 (0.12)
Fast	1.69 (0.26)*	1.60 (0.10)	1.49 (0.15)*
Very fast	2.23 (0.26)*	2.10 (0.28)	1.92 (0.18)*

* Two groups are different from one another at $p < 0.05$.