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# Age-related differences in pelvic and trunk motion and gait adaptability at different walking speeds

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ABSTRACT

This study aimed at investigating age-related changes in gait kinematics and in kinematic adaptations over a wide range of walking velocities. Thirty-four older adults and 14 younger adults walked on a treadmill; the treadmill velocity was gradually increased in increments of 0.2 miles/hour (mph) (1.1–1.9 mph) and then decreased in the same increments. Pelvic, trunk, upper limbs and lower limbs angular total ranges of motion (tROM), stride time, stride length, and step width were measured. The older adults had lower pelvic, trunk tROM and shorter strides and stride time compared with the younger adults. As the treadmill speed was gradually increased, the older adults showed an inability to change the pelvic list angular motions (3.1 ± 1.3° to 3.2 ± 1.4°) between different walking velocities, while the younger adults showed changes (5.1 ± 1.8° to 6.3 ± 1.7°) as a function of the walking velocity. As the walking velocity increased, the older adults increased their stride length (from 57.0 ± 10 cm to 90.2 ± 0.1 cm) yet stride times remained constant (from 1.17 ± 0.3 sec to 1.08 ± 0.1 sec), while the younger adults increased stride length and reduced stride times (from 71.4 ± 10 cm to 103.0 ± 7.9 m and from 1.45 ± 0.2 sec to 1.22 ± 0.1 sec, respectively). In conclusion, the older adults were unable to make adaptations in pelvic and trunk kinematics between different walking speeds (rigid behavior), while the younger adults showed more flexible behavior. Pelvic and trunk kinematics in different walking speeds can be used as variables in the assessment of gait in older adults.

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## 1. Introduction

In the elderly population, about one-third experience falls (Feder et al., 2000) that result in acute injuries or even death (CDC, 2012). Walking is the major activity during which a large proportion of falls in older adults occurs (Robinovitch et al., 2013), and impaired gait is associated with increased risk of falling (Hausdorff et al., 2001; Toebes et al., 2012; Verghese et al., 2009; Weiss et al., 2013). In fact, age-related deterioration of balance and walking ability affects even independent older adults (Alexander, 1996), however this substantial decline does not become evident until they fall. Thus, an effective way to decrease the number of fall-related injuries may be to identify specific markers that are associated with the deterioration of gait in older adults who have not yet experienced falls. Recognizing these markers would help researchers in understanding the mechanisms related to changes in gait characteristics, as well as assist the medical professional to prescribe an intervention that could prevent the occurrence of falls at early stages.

In this study we use a dynamic approach (Barak et al., 2006; Wagenaar and Beek, 1992) to identify and classify age-related changes in gait kinematics, with an emphasis on adaptations in pelvic and trunk kinematics. Possible mechanisms for changes in gait parameters such as shorter stride length and compensatory higher frequency with aging include muscle weakness (McGibbon et al., 2001), balance impairments (Wolfson et al., 1995), and reduction of energy cost (Holt et al., 1995). Some of these deficits may be related to impaired pelvic and trunk motion. Decreased pelvic and trunk motion may change gait patterns, reduce stability and stride length, and increase energy cost. However, little has been studied

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on the relation between pelvic motion and trunk motion during gait, or on the ability of the pelvis and trunk to adapt to changes in walking conditions (i.e. various walking speeds) in terms of flexibility and stability. In the current research we studied the flexibility and stability of gait by systematically manipulating walking velocity. We define flexibility as the ability to adapt to a different gait kinematics following changes in walking speeds, as well as the ability to make a transition (i.e., adaption of the gait at different walking speeds) between different walking conditions (operationalized as mean range of motion during the strides). Stability is defined as the low variability between strides within a specific walking speed (operationalized as mean standard deviation between strides). Older fallers showed significantly greater step frequency, smaller stride lengths and times, smaller center-of-mass lateral sway, smaller ankle plantar flexion, hip extension during push-off, and higher variability compared with the non-fallers (Barak et al., 2006). Few studies have concentrated on age-related changes and adaption strategies in pelvic and trunk kinematics at various walking speeds. In this study we analyze the pelvic transverse rotation and pelvic list (i.e., pelvic drop of the swinging leg), as it was shown that these help control Center of Mass (COM) translation during walking, and since they are important for reducing energy consumption (Lin et al., 2014). Further, we studied the trunk rotation, as it was found that it helps compensate for pelvic angular movements (Patla et al., 1999). We aimed to study walking at different walking speeds, since this would put different demands on the control of pelvic and trunk movements that stabilize and maintain posture. It is well known that there is an age-related decrease in pelvic and trunk motion. Therefore, spatiotemporal adaptations will most likely be needed to diminish energy costs and reduce COM motion during gait in older adults. If this is true, then changes in gait patterns such as reduced step length, step times and arm movements should support this premise.

We predicted that compared with young adults, older adults will show the following characteristics: (1) reduced step length and increased step width in all walking speeds; (2) reduced lower limbs and upper limbs total range of motion (tROM) in the sagittal plane; (3) reduced pelvic transverse rotation and pelvic list; (4) reduced ability to make a transition between different walking conditions (i.e., reduced adaptability/flexibility); (5) a general reduction in gait adaptability and increased variability (i.e., hypo-stability) in different walking velocities.

## 2. Subjects and methods

### 2.1. Subjects

Thirty-four community-dwelling older adults and 14 young adults were recruited (mean age 80 ± 5.3 years old vs. 26.4 ± 0.9, height 158.3 ± 9.3 cm vs. 168.9 ± 10.6 cm, weight 66.9 ± 12.8 kg vs. 65.6 ± 13.8 kg, BMI 26.6 ± 4.1 vs 22.7 ± 2.6, respectively) (see Table 1). Eligibility criteria for the older adults were: 70 years or older; independently ambulatory; Mini-Mental Score higher than 24; no known neurological disorders; no metastatic cancer. The fourteen young adults were recruited from the university population. Subjects were excluded if they had severe cardiovascular or respiratory disease, or if they had undergone total hip or knee replacement. The study was approved by the Helsinki Committee of the Barzilai University Medical Center, Ashkelon, Israel (ClinicalTrials.gov Registration number #NCT01439451).

### 2.2. Study protocol

After signing an informed consent statement, the subjects were instructed to walk on a treadmill, wearing their own walking shoes, with their hands free to swing; there were no handrails on the treadmill. Familiarization with the treadmill was achieved for each subject by four to seven minutes of walking prior to data collection. To prevent injury if loss of balance occurred during the treadmill walking, the subject wore a loose safety harness that could arrest the fall, but that allowed the subject to walk comfortably without suspension (Fig. 1). The instructions given to the subjects were: "Walk as naturally as possible at your preferred stride frequency". The treadmill's walking speed was systematically increased from 1.1 miles per hour (mph) to 1.9 mph in steps of 0.2 mph, and subsequently, decreased in similar increments. Each walking speed condition was maintained for 35–40 sec to 5–10 sec for subject adaptation to a new speed condition and then 30 sec for motion data collection. Participants reported their

**Table 1**
Subjects characteristics: descriptive statistics and group comparisons. Values are means ± SD (95% confidence interval for means).

| Variable | Old ($N = 34$) | Young ($N = 14$) |
|---|---|---|
| Age (year) | 80 ± 5.3 | 26.4 ± 0.9 |
| % Female* | 72.1% | 57.1% |
| Number drugs/day | 4.1 ± 2.8 | 0 |
| Height (cm) | 158.3 ± 9.3 | 168.9 ± 10.6 |
| Weight (kg) | 66.9 ± 12.8 | 65.6 ± 13.8 |
| BMI (cm/m$^2$) | 26.6 ± 4.1 | 22.7 ± 2.6 |
| POMA | 26.7 ± 1.6 | 28 |
| MMSE | 28.3 ± 1.7 | 30 |

Note: *p*-value compares baselines means in the two groups and, unless otherwise indicated, are based on *t*-test or chi-square.
cm = centimeters, kg/m$^2$ = kilograms per meter squared; POMA = Performance-oriented mobility assessment; MMSE = Mini-Mental State Examination.
* *P*-value based on Wilcoxon signed rank test and Mann–Whitney *U* test.


[redacted]

**Fig. 1.** The experimental set up.

preferred walking speed during the systematic increases of the treadmill speed. If the subject felt unsafe during one of the walking conditions the treadmill speed was then decreased to a lower walking speed, and the data for the walking speed where the subject felt unsafe were not included in the data analysis.

### *2.3. Measured and calculated parameters*

Three-dimensional (3D) kinematic data were collected through the Ariel Performance Analysis System (APAS, Ariel Dynamics Inc., CA, USA), which can provides kinematic analysis of a motion sequence. Two video cameras were placed at an angle of 45°, approximately 7 m in front of the treadmill, and they recorded the motion of 8 reflective markers placed on the body. The markers were attached to the midline of the anterior aspect of ankle joints, the Anterior Superior Iliac Spines (ASIS), the shoulders' acromion process, and the radial styloid process. The marker locations were sampled simultaneously by the cameras at a frequency of 60 Hz. Views from the two cameras were mapped onto a 3D coordinate system by the computer using an internal direct linear transformation algorithm. The data were grabbed, digitized, transformed, and smoothed using low-pass filter (Butterworth second-order forward and backward passes) with a cut-off frequency of 5 Hz. The APAS was shown to be valid and reliable, with a system mean point estimate error of less than 3.5 mm, 1.4 mm mean linear error, and 0.26° mean angular error (Klein and DeHaven, 1995).

Gait kinematics parameters were calculated using our own code written in Matlab (Math Works Inc., Cambridge, MA, USA). The gait cycle (stride time) was defined from toe-off to toe-off. Using the ankle markers' temporal data ($x$, $y$, $z$ coordinates) and by visual inspection of the video (using the time stamp), it was found that the toe-off corresponded to the peak vertical velocity of the ankle (velocity in the $y$ direction). Therefore, our code was designed to find these peak velocities (Fig. 2). Using a similar method, it was found that when the ankle reached the most forward value this corresponded to a heel strike (Fig. 2). Therefore, an algorithm was implemented to identify the toe-off and heel strike automatically. Once these events were identified, it enabled the calculation of stride time, length, and width (see Fig. 2). The rest of the gait parameters were identified and calculated with similar algorithms. The total lower limbs range of motion (tROM) angles in the sagittal plane was detected using ASIS and ankle joint markers. The lower limb angle was defined as the angle from the transverse vector to a vector from the ankle to the ASIS. The upper limbs' angle was measured in the sagittal plane using a vector from the radial styloid process marker to the shoulder acromion markers, and was measured with respect to the transverse vector. After computing the lower limbs' and upper limbs' angle, the tROM was found using peak-to-peak during each gait cycle. Pelvic and trunk transverse rotation was detected through the ASIS and acromion markers movement, respectively, with respect to the frontal plane (defined by a vector from the right side to the left side). Similar to the upper limbs and lower limbs, the pelvic and trunk tROM in degrees in the transverse plane at each stride were calculated. In addition, the maximal (peak-to-peak) pelvic list tROM in degrees (i.e., the pelvis drops away from the stance leg toward the swing leg involving the alternate rotation of the pelvis up and down in relation to the body's central axis at each stride was also calculated (Fig. 3). The values presented are average values, as well as the average standard deviation (SD) of about 30 strides (i.e., 60 steps) for each walking speed.

### *2.4. Statistical analysis*

For statistical calculations, the PASW Statistics version 15.0 was used (Somers, NY, USA, version 15). Mean values of the dependent variables were computed from the group data. The standard deviation of each group was averaged from each subject's sum of strides at each speed condition (about 30 strides for each walking speed). To evaluate if there was a hysteresis effect during the increasing and subsequently decreasing walking speeds, an analysis of variance (ANOVA) for repeated measures with one within-group factor (2 levels: increasing versus decreasing walking speeds) was applied for each age group separately (see Figs. 4-6). The dependent variables were: stride time, length, and width; lower limbs and upper limbs sagittal plane tROM; pelvic and trunk transverse tROM; pelvic list; and, the medio-lateral movement of COM (ML-COM). There were no significant hysteresis effects for either group, thus for age comparisons only data of increasing speed conditions were analyzed. In addition, for each walking speed we found no significant differences between the right and left lower limb sagittal plane ROM or between the right and left upper limbs, thus the average values of right and left limbs were calculated and analyzed in the current study.

To evaluate age-related differences in gait dynamics, a 2-way between group ANOVA for repeated measures was carried out to evaluate the effects of age (young vs. old) and walking speeds (5 walking speeds, from 1.1 mph to 1.9 mph), as well as the interaction effect between age groups and walking speeds. In cases of a significant finding, a *post hoc* analysis was carried out to determine whether there were within-group significant differences in the dependent variables between different walking speeds (1.1 mph, 1/3 mph, 1.5 mph, 1.7 mph, and 1.9 mph). The level of statistical significance was set at $P < 0.05$.

## 3. Results

Thirty-four older and 14 younger adults underwent the study protocol. Of those, all the younger adults were able to walk at all walking speeds, whereas 5 of the 34 older adults were unable to complete the trial and reported that they felt unsafe/unstable at the 2 highest walking speeds (1.7 mph and 1.9 mph). The data from their "successful" trials were included for analysis. Preferred walking speeds were different between the healthy older and the young adults (1.3 mph vs. 1.9 mph, $p < 0.001$). The main effects of age in 5 different walking speeds as the between-group factor are reported in Table 2. There were age-group differences for all the dependent variables of gait at all walking speeds, apart from the upper limbs' sagittal plane tROM (Table 2).

### *3.1. Stride time*

A significant main effect of age was found for stride times. The older adults had shorter stride times at all walking speed conditions compared with the younger adults ($p < 0.001$, see Table 2). A significant main effect of walking speed was found for stride time for the younger group (Fig. 4(1)). Visual inspection revealed that the younger adults showed an almost linear decrease in stride time from 1.1 mph to 1.9 mph, then a linear increase from 1.9 mph to 1.1 mph. *Post hoc* analysis for speed conditions revealed that at 1.9 mph, stride time was significantly shorter compared with walking speed conditions of 1.5 mph (decreased and increased) and lower speeds ($P < 0.05$) for the young group, while in the older adults it was not. For the SD's of the stride times, there was no significant main effect of speed in either age group.

### *3.2. Stride length*

A significant main effect of age was found for stride length. The older adults had shorter strides at all walking speed conditions compared with the younger adults ($p < 0.001$, see Table 2). A

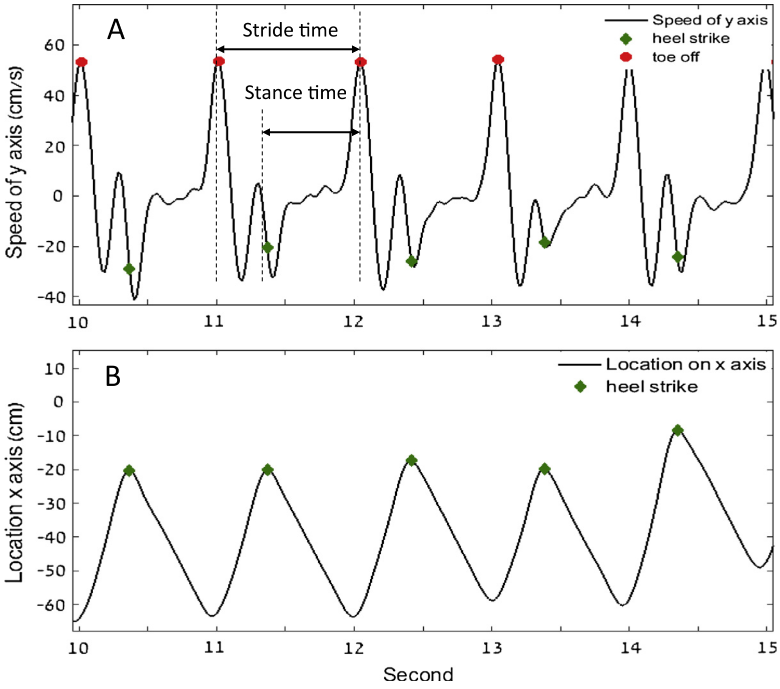


**Fig. 2.** Example of results from the automatic dedication of heel strike (green diamond) and toe off (red dot), and calculation of gait cycle time and stride time. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

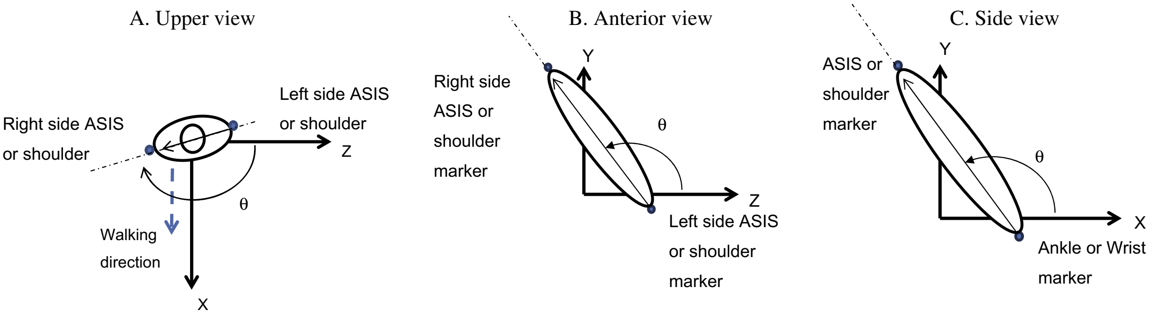
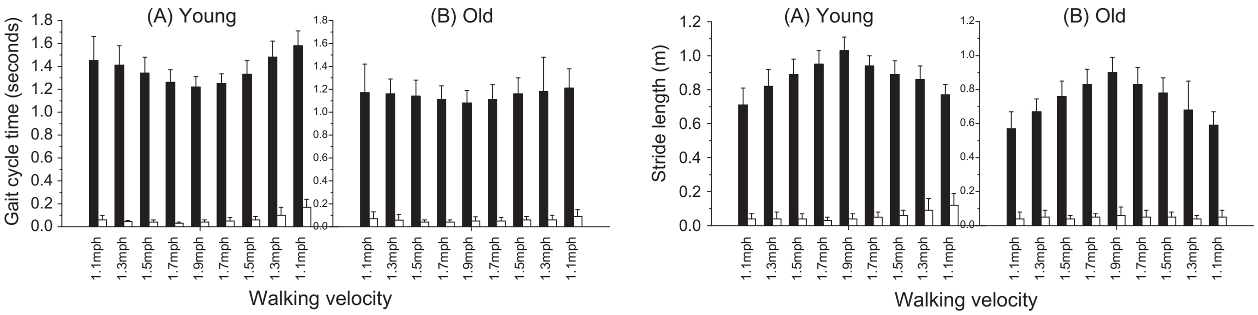


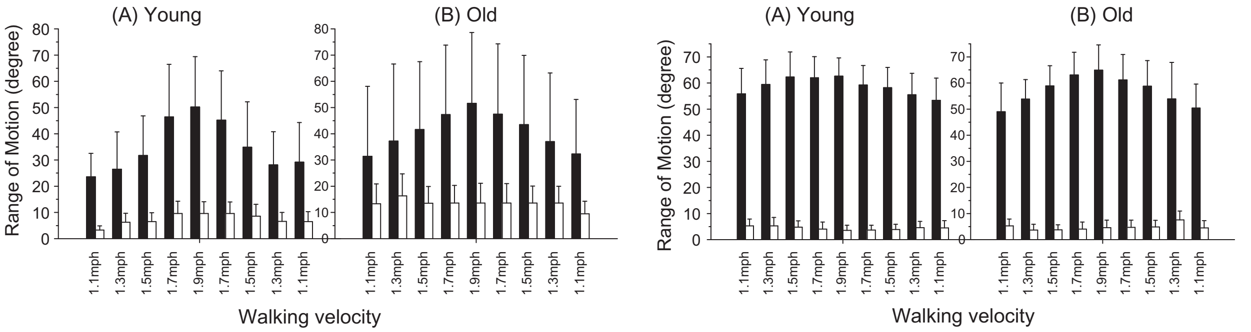
**Fig. 3.** (A) Definition of the shoulder and pelvis angles on the transvers plane ($X, Z$). e.g. when $\theta$ equal zero this mean that an arrow form left marker to right marker is pointing in the $Z$ direction. (B) Definition of the pelvic and shoulder angle as projected on the coronal plane ($Y, Z$). e.g. when $\theta$ equal 180 this mean that line from the left ASIS to right ASIS is parallel to the ground. (C) Definition of the leg and arm angles as projected on the Sigatal plane ($X, Y$), e.g. when $\theta$ equal 90 this mean that line from the ankle to the ASIS is vertical to the ground.



(1) Stride time (Gait cycle)

(2) stride length

**Fig. 4.** Stride time (seconds) (1), and stride length (meters) (2) at each walking speed for old and young adults and its standard deviation for old and young adults who were instructed to walk on a treadmill at a wide range of increasing and decreasing velocities (i.e., 1.1–1.9 mph). In general young subjects (Panel 1A) shows a gradual transition between walking speeds (flexible behavior) in stride time, while older adults (panel 1B) show minimal transition behavior between walking speeds (a more rigid behavior); For the stride length both age groups show shows gradual transition (more flexible behavior, Panel 2A and B) with little change of the standard deviation for both age groups. Note: mph = mile per hour.



(1) Arms tROM angle

(2) Leg tROM angle

**Fig. 5.** Arms (1) and leg (2) total range of motion angle (tROM) in the sagittal plane at each walking speed and its standard deviation for old and young adults who were instructed to walk on a treadmill at a wide range of increasing and decreasing velocities (i.e., 1.1–1.9 mph). In general both age groups subjects show gradual transition in arms (Panel 1A and B) between walking speeds (flexible behavior) with higher standard deviation for older adults. Panel (2A and B) shows gradual transition in leg swing with little change of the standard deviation for both age groups. Note: mph = mile per hour.

significant main effect of walking speed was found for stride length. Visual inspection showed that both age groups had an almost linear increase in stride length from 1.1 mph to 1.9 mph, than linear decrease from 1.9 mph to 1.1 mph (Fig. 4(2)). *Post hoc* analysis for speed conditions revealed that at 1.9 mph stride length was significantly longer compared with all other speed conditions, for both age groups ($P < 0.01$). An additional *post hoc* analysis for speed conditions revealed that the SD's of stride lengths of the older adults was significantly larger at 1.9 mph compared with all other walking speeds ($P < 0.05$), whereas in the younger adults it was not.

### 3.3. Stride width

A significant effect of age was found for stride width. At all walking speed conditions, the older adults had a wider stride width ($p < 0.001$, Table 2). No significant differences in stride width was shown in either group, and also not for stride width SD's with increasing walking speed.

### 3.4. Lower limbs and upper limbs sagittal plane tROM

There were no age-related differences for upper limbs tROM for all walking speeds, while lower limbs tROM was significantly smaller in the older compared with the younger adults at the lower walking speeds only (1.1 mph and 1.3 mph, Table 2, $p < 0.05$). Visual inspection showed an almost linear increase in lower limbs and upper limbs tROM from 1.1 mph to 1.9 mph for both age groups than linear decrease from 1.9 mph to 1.1 mph (Fig. 5(1) and (2)). *Post hoc* analysis for speed conditions revealed that at 1.9 mph, upper limbs tROM in both age groups was significantly higher compared with speed conditions of 1.5 mph and lower (Fig. 5(1A) and (1B), $P < 0.05$). An additional *post hoc* analysis revealed that at 1.9 mph, lower limbs tROM angles was significantly higher with speed conditions of 1.1 mph for the younger group subjects ($P < 0.05$) and significantly higher with speed conditions of 1.3 mph and 1.1 mph for the older adults (Fig. 5(2A) and (2B), $P < 0.05$). A significant main effect of age group was found for SD's in upper limbs tROM but not for lower limbs tROM, where the older adults showed a larger variability in upper limbs tROM at all walking speeds compared with the younger adults.

### 3.5. Pelvic transverse and pelvic list tROM

A significant main effect of age was found for pelvic transverse and pelvic list tROM's. The pelvic transverse and pelvic list tROM's were smaller in the older compared with younger adults at all walking speeds (Table 2, $P < 0.005$). *Post hoc* analysis revealed no significant main effect of walking speed on pelvic transverse tROM, either for the younger or the older adults (Fig. 6(1A) and (1B)). (Fig. 6(2A)). *Post hoc* analysis for speed conditions revealed that at 1.9 mph, pelvic list tROM was significantly higher compared with speed conditions of 1.3 mph and 1.1 mph (Fig. 6(2A), $P < 0.05$) for the younger adults only (Fig. 6(2B)). No significant main effect of age was found for SD's in pelvic transverse or pelvic list tROM.

We also calculated the medio-lateral movement of COM (ML-COM) at different walking speeds. There were no age-related

**Table 2**
Age group means and standard deviations of gait characteristics presented for each velocity level separately. The results for both young subjects ($N = 14$ for all velocity levels) and older adults ($N = 34$).

| | 1.1 mph | | 1.3 mph | | 1.5 mph | | 1.7 mph | | 1.9 mph | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Old | Young | Old | Young | Old | Young | Old | Young | Old | Young |
| Stride time (sec) | 1.17 ± 0.3$^{***}$ | 1.45 ± 0.2 | 1.16 ± 0.1$^{***}$ | 1.40 ± 0.2 | 1.14 ± 0.1$^{***}$ | 1.34 ± 0.1 | 1.11 ± 0.1$^{***}$ | 1.26 ± 0.1 | 1.08 ± 0.1$^{***}$ | 1.22 ± 0.1 |
| Stride length (cm) | 57.0 ± 10$^{***}$ | 71.4 ± 10 | 67.2 ± 7.5$^{***}$ | 81.7 ± 10.3 | 76.1 ± 9.3$^{***}$ | 89.7 ± 9.6 | 83.5 ± 9.2$^{***}$ | 94.5 ± 8.0 | 90.2 ± 0.1$^{***}$ | 103.0 ± 7.9 |
| Stride width (cm) | 17.1 ± 4.5$^{*}$ | 15.4 ± 2.6 | 17.6 ± 3.4 $^{*}$ | 15.2 ± 2.8 | 17.4 ± 3.4$^{*}$ | 14.9 ± 2.6 | 17.5 ± 3.6$^{*}$ | 15.0 ± 2.8 | 17.6 ± 3.7$^{*}$ | 15.0 ± 2.7 |
| Legs sagittal plane tROM (°) | 49.0 ± 10.9$^{*}$ | 55.9 ± 9.7 | 53.8 ± 7.5$^{*}$ | 59.4 ± 9.5 | 58.8 ± 7.7 | 62.3 ± 15.1 | 63.1 ± 8.8 | 62.0 ± 8.1 | 64.9 ± 9.6 | 62.6 ± 7.0 |
| Arms sagittal plane tROM (°) | 31.4 ± 26.7 | 23.6 ± 8.9 | 37.2 ± 29.4 | 26.5 ± 14.2 | 41.6 ± 25.9 | 31.7 ± 15.1 | 47.3 ± 26.5 | 46.4 ± 20.1 | 51.6 ± 27.0 | 50.2 ± 19.2 |
| Pelvic transverse tROM (°) | 5.7 ± 2.2$^{***}$ | 10.4 ± 3.3 | 6.0 ± 2.2$^{***}$ | 9.9 ± 4.3 | 5.7 ± 1.8$^{***}$ | 9.5 ± 3.5 | 5.6 ± 1.8$^{***}$ | 9.1 ± 2.9 | 5.9 ± 2.0$^{***}$ | 9.2 ± 3.2 |
| Pelvic list tROM (°) | 3.1 ± 1.3$^{***}$ | 5.1 ± 1.8 | 3.2 ± 1.3$^{***}$ | 5.5 ± 2.0 | 3.2 ± 1.3$^{***}$ | 5.6 ± 1.8 | 3.1 ± 1.4$^{***}$ | 6.1 ± 1.7 | 3.2 ± 1.4$^{***}$ | 6.3 ± 1.7 |
| Trunk transverse tROM (°) | 4.5 ± 1.9$^{***}$ | 7.3 ± 2.4 | 5.3 ± 2.3$^{***}$ | 8.2 ± 2.6 | 6.0 ± 2.2$^{***}$ | 9.2 ± 2.8 | 6.9 ± 2.5$^{***}$ | 10.7 ± 3.4 | 7.5 ± 2.6$^{***}$ | 11.9 ± 4.3 |

Note: mph = mile per hour; sec = seconds; cm = centimeters; tROM (°) = total range of motion in degree.
[*] $p < 0.05$.
[***] $p < 0.005$.

differences in ML-COM movements in different walking speeds, i.e., 5–4.2 cm in younger adults vs. 4.7–4.2 cm in older adults.

### *3.6. Trunk transverse tROM*

A significant main effect of age was found for trunk transverse tROM. Trunk transverse tROM angles were smaller at all walking speeds in the older compared with the younger adults (Table 2, $P < 0.005$). Trunk transverse rotation angles of the young adults showed an almost linear decrease from 1.1 mph to 1.9 mph, and a linear increase from 1.9 mph to 1.1 mph, while for the older adults this parameter did not change with speed. *Post hoc* analysis for speed conditions revealed that at 1.9 mph, trunk transverse rotation angles of the younger adults was significantly higher compared with speed conditions of 1.5 mph and lower. For the older adults, however, trunk transverse rotation angles at 1.9 mph were significantly higher compared with speed conditions of 1.1 mph. In addition, no significant main effect of age group was found for trunk transverse tROM SD's.

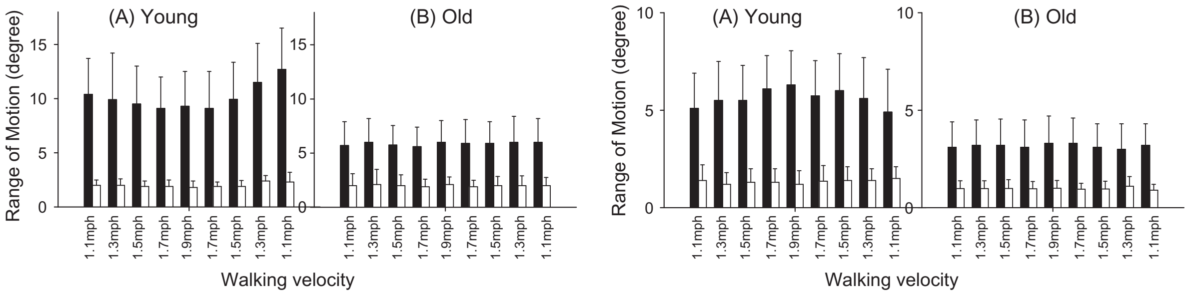
## 4. Discussion

In the testing protocol the subjects walked at a wide range of walking speeds. Similar to previous studies, our data also suggest that most of the biomechanical parameters depend on gait speed (Barak et al., 2006; Bejek et al., 2006; Guimaraes and Isaacs, 1980; Wagenaar and Beek, 1992). The differences in gait between younger and older subjects presented in the literature with respect to the spatio-temporal parameters of the stride are confirmed in this study (Alexander, 1996; Doyo et al., 2011; Guimaraes and Isaacs, 1980; Lin et al., 2014). We were able to identify age-related changes of gait function through differences in the kinematics, as well as in the dynamic behavior of pelvic and trunk angular motion patterns. In the present study, the older adults had an average of 40% smaller transverse pelvic rotation, 44% smaller pelvic list, and 36% smaller trunk transverse rotation. However, compared with young's older adults demonstrated a significantly shorter stride length, ranged from 12.5% at the highest walking speed and 20% at the slowest walking speed (Table 2). This indicates that the decrease in stride length occurred due to decreased pelvic rotation, which may be affected by the natural reduction of the lumbar spine mobility that occurs with aging. The older subjects in the present study compensated for reduced pelvic mobility by the lower limbs tROM in the sagittal plane. Bejek et al. (2006), however, found that decreased hip joint or knee joint ROM's in patients with unilateral osteoarthritis was compensated for in part by the pelvic movements. It should be noted, however, that the different average height of the two groups in the present study might account for this difference. To cancel the effect of subject height, we divided the stride length by the average group height (since the lower limbs are proportional to the height). This resulted in a change of approximately 15% at the lowest walking speed and about 7% at the highest speed. The lower limbs tROM in the sagittal plane, however, was 12% higher for the young adults at the slowest walking speed, but there was no difference at the highest walking speed. These results suggest that the lengthening of the strides in the young adults resulted from the contribution of the pelvic transverse rotation (i.e., "pelvic step").

Malatesta et al. (2003) found greater energy expenditure in older adult while walking, however they did not find a significant correlation between the energy cost and gait instability. The greater energy expenditure was associated with walking movements, and was related to mechanical work or neuromuscular factors. Since the pelvic motion was not measured, they were unable to conclude what mechanism is related to the greater energy expenditure. Malatesta et al. (2003) suggested that younger adults used pelvic transverse rotation as a strategy to minimize COM vertical movements during the double support phase. Older adults in the present study controlled the vertical COM movement during gait by using shorter strides. The results of the present study also show a greater pelvic list in the younger compared with the older adults. Pelvic list is a mechanism to lower the position of the COM during the single limb stance phase, and thus decreases the COM height at its highest point during the gait cycle. Pelvic list also contributes most significantly to the medio-lateral displacement of the COM in the coronal plane (Lin et al., 2014). Both pelvic transverse and pelvic list rotations were suggested to be used as strategies to control/reduce vertical COM motion, and thus reduce energy costs of gait. Any movement of the COM, from side-to-side or up and down, will waste energy (Lin et al., 2014; Malatesta et al., 2003). To improve energy efficiency, the younger adults controlled their body COM motion using pelvic rotations, while the older adults controlled their body COM motion using smaller strides. The present study suggests that (1) older adults did not preserve the ability of using the pelvic angular motion during gait; the smaller transverse pelvic and pelvic list movements in the older adults were related to a smaller strides ($r = 0.56$, $p < 0.001$ and $r = 0.43$, $p < 0.003$, respectively); (2) Smaller strides were found to reduce decreased COM vertical excursion, ground reaction force (GRF), shock attenuation and energy absorbed at the ankle, knee and hip joints (Schubert et al., 2014). Thus the older adults in the present study used the smaller stride strategy to reduce COM vertical movement, with the aim of also reducing the GRF, which decreases balance challenges during gait; (3) Muscle co-activation around the pelvic and trunk might cause joint stiffening and limits the degrees of freedom needed for walking (Woollacott and Shumway-Cook, 1990), as seen in the current study. Muscle co-activation was also suggested as increasing the mechanical work of walking (Malatesta et al., 2003). Massaad et al. (2010) found that excessive energy consumption is mainly due to extra positive muscle work needed to lift the COM.

Our study revealed that even healthy older adults walk with wider strides at all walking speeds. Stride width was suggested as an early marker of reduced stability during walking and a measure of balance control in gait (Maki, 1997). Studies of stride width are controversial; while Maki et al. (1994) found that older adults who fall walk with wide strides, Guimaraes and Isaacs (1980) found that in order to control lateral stability older adults who fall walk with narrow strides. Sekiya et al. (1997) and Hausdorff et al. (2001) measured within-subject stride width standard deviation and coefficient of variation, and found that both increase with age and are greater in fallers than non-fallers. In the present study the ML-COM movements between young and older adults were similar at all walking speeds (5–4.2 cm vs. 4.7–4.2 cm, respectively). These results suggest that older adults had "used" a smaller portion of their ML base of support compared with the younger adults, suggesting that this was probably due to safety reasons.

We also studied kinematics of treadmill ambulation during walking in different speed conditions, with a focus on pelvic rotations. Similar to our results, Hirasaki et al. (1999) found that when young subjects increased walking speeds, they increased their stride length and reduced stride times. Contrary to the younger adults, the older adults in the present study increased only stride length, while maintaining the same stride times. Regarding pelvic motion, our results revealed that the older adults adopted a more rigid behavior (i.e., no transition behavior) in the pelvic and trunk kinematics, while the younger adults showed a gradual transition in pelvic list (i.e., an increase rather than a decrease) and in pelvic transverse trunk rotations (i.e., a decrease rather than an increase) between different walking speeds (i.e., transition behavior/flexible behavior). These results suggest that the two groups modified their



(1) Pelvic transverse tROM

(2) Pelvic list tROM

**Fig. 6.** Pelvic transverse total range of motion (tROM) (1), and pelvic list tROM (2) in degrees, at each walking speed and its standard deviation for old and young subject's adults who were instructed to walk on a treadmill at a wide range of increasing and decreasing velocities (i.e., 1.1–1.9 mph). In general young subjects (Panel 1A and 2A) shows for low rigidity scores a gradual transition between walking speeds (flexible behavior) while older adults (panel 1B and 2B) shows high rigidity (no transition behavior) with higher standard deviation. Note: mph = mile per hour.

stride length differently with the changes in walking speed. While the younger adults modified stride length by controlling both lower limbs ROM as well as pelvic and trunk angular motion (i.e., more flexible behavior), the older adults modified their stride length by adapting only lower limbs ROM movement, with no corresponding change in pelvic and trunk angular motion (i.e., rigid behavior). Similar to our results, Wagenaar and Beek (1992) showed that with the increase in the walking speeds, young subjects showed a gradual decrease and not an increase in pelvic transverse tROM. This is somewhat surprising; we expected that the increase in walking speed and step length would be accompanied by increased pelvic transverse rotation, but in the young adults it was associated in particular with increased rotations about the anterior-posterior axes (pelvic list, see Fig. 6) and with an increase in trunk transverse movement. This finding remains open for further investigation. Future research should determine if the excessive arm movements during the high walking speeds in younger adults are related to the reduction transverse pelvic rotation and the concurrent increase in trunk tROM.

This study has several limitations. First, the data came from a fairly small sample that was drawn from a defined, relatively healthy community-based population; these results cannot be generalized to extremely weak or institutionalized elderly persons. Further study should involve larger sample sizes and less healthy populations of older adults. Second, the question of whether the characteristics of pelvic and trunk kinematics during treadmill walking provide a good estimate of their characteristics during over-ground gait may be a drawback of this study's protocol. One difference between treadmill and over-ground walking is the absence of visual flow, which also occurs in over-ground walking in a large featureless space, where visual flow is minimal. Another difference is that during treadmill walking the ground is moving under the feet, thus push-off leg power is less necessary. Other studies indicate that vertical trunk translation is larger during treadmill walking than over-ground walking (Murray et al., 1985). However, after a short training the differences between treadmill and over-ground walking became insignificant (Murray et al., 1985). This suggests that the characteristics of normal locomotion can be adequately studied on a treadmill. Furthermore, Moe-Nilssen and Helbostad (2005) suggested that when differences in gait parameters during over-ground walking between populations demonstrate different walking speeds, the results may be biased. Thus, using treadmill walking at different walking speeds may lead to the ability to compare age-related changes in coordination patterns that are not related to a difference in gait speed. The results of the present study suggest that walking speed is an important independent variable in the evaluation of older adults' gait and can be used as a basis for the classification of gait deficits (see Figs. 4-6).

## 5. Conclusions

Our testing protocol of manipulations of walking speed on a treadmill has led to the identification and classification of different patterns in walking, in terms of flexibility and stability between the two groups. We found that while the younger adults modified their stride length using pelvic motion, the older adults did not. The older adults in the present study had a general inability to make a transition in pelvic angular motions between different gait speeds (reduced adaptability/flexibility), with no concurrent impairment in limb angular motion.

## Conflict of interest statement

There are no conflicts of interest to disclose for any of the authors.

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