applied sciences

MDPI

Article

A Comparison of Turning Kinematics at Different Amplitudes during Standing Turns between Older and Younger Adults

Fuengfa Khobkhun [1,*], Mark Hollands [2] and Jim Richards [3]

[1] Faculty of Physical Therapy, Mahidol University, Salaya, Nakhon Pathom 73170, Thailand
[2] Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool L3 3AF, UK; m.a.hollands@ljmu.ac.uk
[3] Allied Health Research Unit, University of Central Lancashire, Preston PR1 2HE, UK; jrichards@uclan.ac.uk
* Correspondence: fuengfa.kho@mahidol.edu

Abstract: It is well-established that processes involving changing direction or turning in which either or both standing and walking turns are utilized involve coordination of the whole-body and stepping characteristics. However, the turn context and whole-body coordination have not been fully explored during different turning amplitudes. For these reasons, this present study aimed to determine the effects of turning amplitude on whole-body coordination. The findings from this study can be utilized to inform the rationale behind fall prevention factors and to help design an exercise strategy to address issues related to amplitude of turning in older adults. Twenty healthy older and twenty healthy younger adults were asked to complete standing turns on level ground using three randomly selected amplitudes, 90°, 135° and 180°, at their self-selected turn speed. Turning kinematics and stepping variables were recorded using Inertial Measurement Units. Analysis of the data was carried out using Mixed Model Analysis of Variance with two factors (2 groups × 3 turning amplitudes) and further post hoc pairwise analysis to examine differences between factors. There were significant interaction effects ($p < 0.05$) between the groups and turning amplitudes for step duration and turn speed. Further analysis using Repeated Measure Analysis of Variance tests determined a main effect of amplitude on step duration and turn speed within each group. Furthermore, post hoc pairwise comparisons revealed that the step duration and turn speed increased significantly ($p < 0.001$) with all increases in turning amplitude in both groups. In addition, significant main effects for group and amplitudes were seen for onset latency of movement for the head, thorax, pelvis, and feet, and for peak head–thorax and peak head–pelvis angular separations and stepping characteristics, which all increased with turn amplitude and showed differences between groups. These results suggest that large amplitude turns result in a change in turning and stepping kinematics. Therefore, when assessing the turning characteristics of older adults or those in frail populations, the turning amplitude should be taken into account during turning, and could be gradually increased to challenge motor control as part of exercise falls prevention strategies.

Keywords: turning amplitude; whole-body-coordination; stepping characteristics; older adults

check for updates

Citation: Khobkhun, F.; Hollands, M.; Richards, J. A Comparison of Turning Kinematics at Different Amplitudes during Standing Turns between Older and Younger Adults. *Appl. Sci.* **2022**, *12*, 5474. https://doi.org/10.3390/app12115474

Academic Editors: Rosa Senatore, Antonio Parziale and Nicole Dalia Cilia

Received: 28 March 2022
Accepted: 26 May 2022
Published: 28 May 2022

1. Introduction

Falls are a major problem in the elderly, usually leading to injury or other potential causes of disability. Patla et al. (1999) [1] observed that falls occur in older individuals during standing turns, while Thigpen et al. (2000) [2] reported similar findings and concluded that swaying is commonly experienced among older individuals when performing 180° standing turns. Other difficulties reported as being associated with turning in older adults have been that slow speed of turning is associated with changing in stepping characteristics in terms of smaller and more frequent steps, and also use of an en-bloc strategy while turning [3,4]. It has been indicated that older adults experience instability, impaired balance and reduced whole-body coordination when compared to younger adults. In addition to age, previous research has indicated that sex has an impact on both postural stability, balance and gait speed; that is, males walk faster than women, which is generally ascribed to the longer step and stride length produced by men [5,6]. However, there have been no reports of the differences between the sexes in turning tasks. Furthermore, turning situations associated with daily activities frequently involve hasty and unpredictable movements with limited time for planning. The lack of planning for movement changes are associated with increase in age and with a decline in turning performance. Khobkhun et al. (2021) [7] reported that changes in speed during turns over 180° have a greater impact on segment onset latencies, intersegmental and stepping characteristics in older group compared to younger group. Furthermore, they reported that the upper and lower body move in an en-bloc strategy when turning at slower speeds in older adults, with the intersegmental angular separations in older adults being less than younger adults at faster speeds. These findings have been previously linked to a shorter stride length and potentially, but not exclusively, to a slower gait speed which may be the consequence of an intentional reduction in turning strategy to compensate for perceived postural instability, which may in turn increase the risk of falling in older adults. However, there is only comparable evidence of spatial perception in young healthy adults from a single study which used a 3D motion analysis system [8], considering participants standing blindfolded on a rotating platform which moved randomly to different angles in clockwise and anti-clockwise directions. The results showed that subjects who were at risk consistently overestimated the amplitude of rotation which they typically, consistently duplicated with their own estimation. The authors concluded that their findings highlighted the importance of dynamic motion in the appropriate perception of spatial orientation. More recent studies have suggested monitoring of turning behavior using Inertial Measurement Units (IMUs) as a solution to assess gait, turning and balance in older adults [7,9,10], as these can be used outside of the laboratory setting. This current study used IMUs to assess the movements of different body segments which provided linear accelerations and Euler segment orientations during turning, which allows the exploration of the modulation of turn amplitude on turning characteristics and the spatiotemporal relationships between the body segments. However, there is a paucity of research that has examined and reported the effect of the amplitudes of turning on whole-body coordination in healthy individuals. Therefore, the aim of this present study was to clarify the effects of turning amplitude on turning characteristics in older adults in comparison to younger adults, which may be related to the risk of falling, which have the potential to be utilized to guide fall prevention strategies, particularly for older adults. Our hypotheses were that changes in turning amplitude affect coordination of the whole-body and stepping characteristics in healthy individuals, and that older adults would adapt their turning strategy during amplitude perturbation, which causes systematic changes in turning behavior. In addition, this protocol should be used when determining the impact of turning on overall coordination, specifically with regard to the diagnosis of turning deficits in older adults. When the proficiency of turning is examined with a focus on segmental independence specific exercises may be recommended on an individual basis to prevent falls.

2. Materials and Methods

2.1. Study Design and Participants

A sample size of 16 participants per group was determined using G*Power statistical software using head onset latency data based on a previous study [5]. This was based on a statistical power of 80% at a significance level of 5% to detect any outcome differences between groups. In order to account for possible dropouts or missing data, a target sample size of 20 individuals per group was used. The inclusion criteria included: (1) to fall within one of two age groups; the younger adult group (aged between 18 to 29 years) and the older adult group (aged between 60 to 75 years); (2) able to understand and follow commands and instructions; (3) be able to walk independently without any assistive devices; (4) score ≥24/30 in the mini-Thai mental state examination, indicating sufficient cognitive ability to engage with the activities [11]. The exclusion criteria included: (1) had a verified clinical diagnosis of a condition that could influence turning movement, for example vestibular dysfunction, and (2) had a comorbidity with severe systemic illness, severe signs and symptoms of musculoskeletal issues, such as having a knee-/hip prosthesis that may influenced turning performance. The study protocol was approved by the institutional ethics committee of the Institutional Review Board on Human Experimentation at Mahidol University, (COA No. MU-CIRB 2021/136.0806) and complied with the ethical standard guidelines of the Declaration of Helsinki. Informed consent was explained, signed and received from all individuals.

2.2. Turning Protocol and Data Collection

Inertial Measurement Units (IMUs) (MVN, Xsens Technologies, Enschede, The Netherlands) were securely strapped to the center of the head, the middle of the thorax, the pelvis, and the center of the left and right feet (Figure 1), which were recorded at a sampling frequency of 100 Hz. Participants were given a visual cue using an animated clock arm which was controlled by LabVIEW software and showed in the projector screen; they were then instructed to reproduce the direction and amplitude of the visual cue. The animation from a video illustrating the turn was presented prior to each trial. Participants were instructed to turn as fast as they could whilst still feeling safe with three randomly determined amplitudes: 90°, 135°, and 180°. For each amplitude the participants had a starting position facing towards the projector screen and were instructed to "turn around". Additionally, the directions were randomly selected to the left and right sides, therefore, a total of six trials for each participant were recorded. Participants were given a 1-min break at the end of each trial or they were permitted to take a rest anytime they needed until they indicated they were ready to start the new trial.

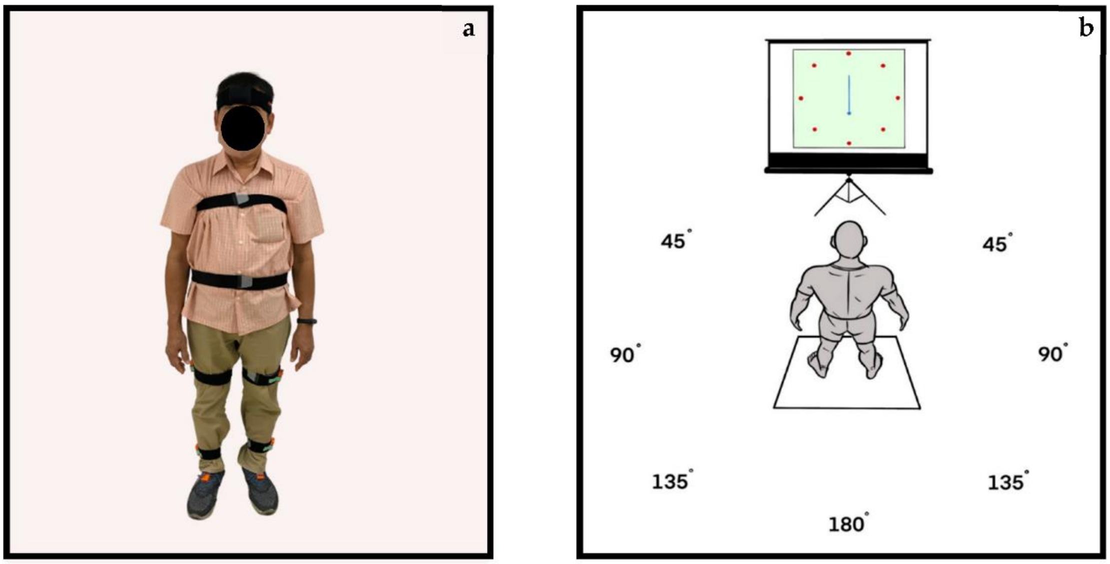

Figure 1. The experimental set up. (**a**) Inertial measurement unit attachment and (**b**) a visual cue using an animated clock arm.

2.3. Data Processing

All dependent variables were analyzed and extracted from MATLAB (R2020b) using a previously validated methodology [7,12,13]. A MATLAB (R2020b) program was used to analyze all measures from the kinematic datasets, using the following as dependent variables as follows;

1. The mean onset time of the head, trunk, pelvis and feet were defined as the yaw angular displacement and velocity profiles by selecting the time which corresponded to the rotation onset for each segment were amplitude greater than 0° and less than

15° with a positive velocity [7]. In addition, the yaw angular displacement was defined as the angle of rotation onset for each segment in the yaw plane.

2. The peak segment angular separations were defined as the angle rotation subtracted between segments (the head and thorax and the head and pelvis), which were used as measures of axial segment and intersegment coordination. Although traditionally, a lack of differences in the timing of axial segment reorientation onset has been used to characterize turning as en-bloc, measuring the rotation of the head with respect to the lower body during the duration of the turn also gives a more complete description of which body segments lead which during the turning rotation [7].
3. Stepping characteristics parameters including step frequency (the number of steps counted divided by step duration), step size (the yaw rotation of the foot during the swing phase which was calculated for each step), and step duration (calculated as the time lapse between step onset and step placement).
4. The turn speed was calculated and defined by the turning amplitude divided by the duration.

2.4. Statistical Analysis

IBM SPSS statistics version 24 was used for all statistical analyses (IBM Corporation, Armonk, NY, USA). Shapiro–Wilk tests were used to determine data distribution, and all data were found to be normally distributed and suitable for parametric testing. In addition, the sphericity of data was considered using Mauchly's test of sphericity, and where the sphericity assumption was violated Greenhouse–Geisser corrections were used. Analysis of the data was carried out using Mixed Model Analysis of Variance (MM ANAOVA) with two factors (2 groups (older and younger groups) × 3 turning amplitudes (90° and 180°, 135°)) and further post hoc pairwise analysis to examine differences between factors. If there were significant interactions between the two components, Repeated Measures Analysis of Variance (RM ANOVA) was used to analyze if there were differences between the three turning amplitudes within the two groups. Furthermore, the effect size was indicated using partial eta squared (η_p^2). The statistical significance level was established at $p < 0.05$, and a Bonferroni adjustment was used for multiple comparisons ($p < 0.004$).

3. Results

Forty-four healthy adults (22 older adults and 22 younger adults) were recruited to this study. However, two individuals from the older adult group did not meet the criteria leading to their exclusion from the study and two individuals from the younger adult group did not complete all the tasks due to their declaration of discomfort during testing. Therefore, 20 participants for each group were gender matched and included in the analysis. Demographic data of the 20 older adults included 10 males and 10 females, aged 67.0 ± 4.37 years, with a mass of 61.8 ± 12.97 kg, height of 1.63 ± 0.09 m, and Body Mass Index = 23.59 ± 4.58 kg/m^2. The 20 healthy younger adults also included 10 males and 10 females, aged 21.59 ± 2.41 years, with a mass of 60.61 ± 9.94 kg, height of 1.64 ± 0.11 m, and Body Mass Index = 23.21 ± 2.91 kg/m^2.

3.1. Segment Onset Latencies

The MM ANOVA revealed that that there were no significant interactions ($p < 0.05$) between groups and turn amplitudes for all segment onset latencies (Table 1). Significant main effects were seen for the group and turn amplitude. The significant main effects between the groups were; head ($F_{(2,40)} = 9.29$, $p = 0.003$, $\eta_p^2 = 0.22$), leading foot ($F_{(2,40)} = 36.59$, $p < 0.001$, $\eta_p^2 = 0.24$) and trailing foot ($F_{(2,40)} = 94.34$, $p < 0.001$, $\eta_p^2 = 0.85$), with the older group showing longer onset latencies. The significant main effects for turn amplitude were the mean onset latencies for all segments with the exception of the trailing foot, specifically; for the head ($F_{(2,40)} = 56.24$, $p < 0.001$, $\eta_p^2 = 0.07$), thorax ($F_{(2,40)} = 52.35$, $p < 0.001$, $\eta_p^2 = 0.55$), pelvis ($F_{(2,40)} = 9.85$, $p < 0.001$, $\eta_p^2 = 0.21$), and leading foot ($F_{(2,40)} = 6.84$, $p = 0.002$, $\eta_p^2 = 0.15$). Further post hoc pairwise comparisons found significant differences in amplitude for the head onset latency between 90° and 180°, 135° and 180°, and 90° and 135°. For the thorax onset latency, significant differences were seen between turn amplitudes at 90° and 180°, 135° and 180°, and 90° and 135°, and for the pelvis onset latency between turn amplitudes at 90° and 135°, and 90° and 135°, with the leading foot also showing significant differences between 90° and 180° (Table 2 and Figure 2). Onset latencies were shortest during the smallest amplitude (90°) and longest during the largest amplitude (180°).

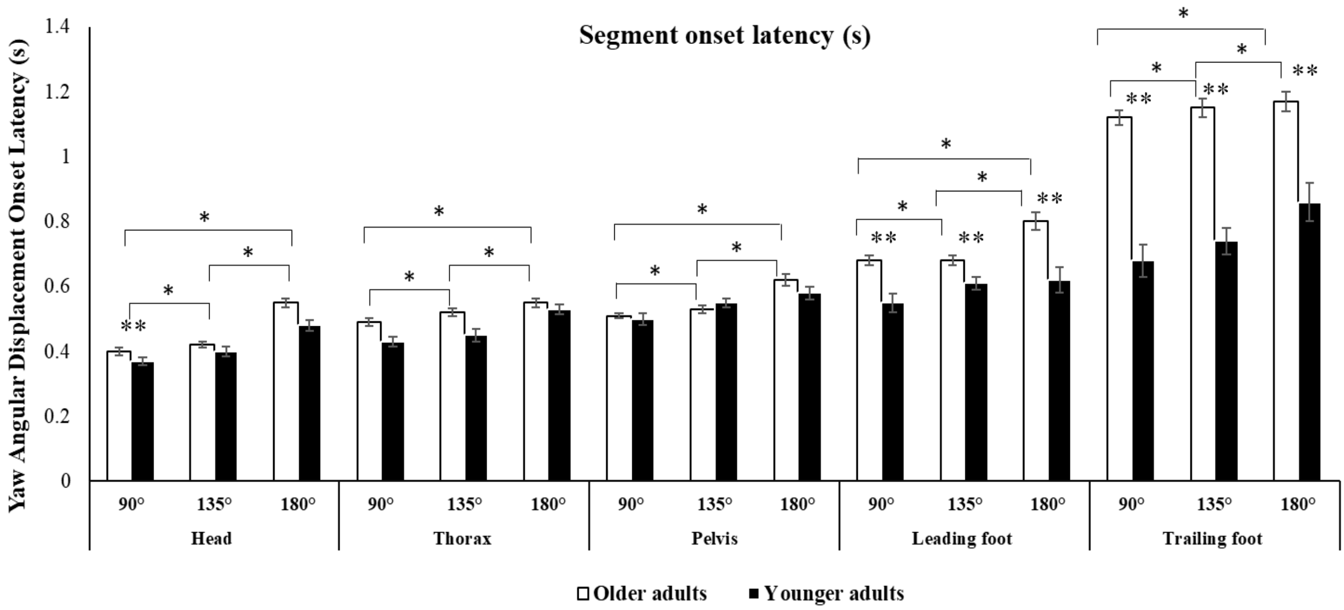

Figure 2. A bar chart demonstrating the mean onset latencies of angular displacement with turn amplitudes. The significant main effect of turn amplitude was found on the timing of onset for all segments. ** Denotes main effects of group from Mixed Model Analysis of Variance. * Denotes main effects of turning amplitude from Mixed Model Analysis of Variance.

3.2. Intersegmental Coordination

In the case of intersegmental coordination, there were no significant interactions between groups and turn amplitude seen in the MM ANOVA. A significant main effect was seen for group for peak head–pelvis angular separations ($F_{(2,40)} = 13.26$, $p < 0.001$, $\eta_p^2 = 0.11$), with the older group showing significantly greater ($p < 0.001$) turn amplitude at 90°, 135° and 180 degrees with differences in peak head–pelvis angular separation of 10°, 13.6° and 18.8°, respectively. Furthermore, the older group showed fewer peak segment angular separations than the younger group. In addition, a significant main effect was seen for turn amplitude for peak segment angular separations for both peak head–thorax and peak head–pelvis ($p < 0.001$), Table 1. Further post hoc pairwise comparisons for turning amplitude showed significant differences between the 90° and 180° turn peak head–pelvis angular separation ($p < 0.004$), showing that peak segmental separation increased with an increase in turn amplitude (Table 2 and Figure 3).

Table 1. Shows the mean and standard deviations (SD) for turning variables, as well as the interaction between group and turning amplitude, as determined by Mixed Model Analysis of Variance.

Variables	Older Adults Group (n = 20)			Younger Adults Group (n = 20)			Main Effect	
	90°	135°	180°	90°	135°	180°	Group Effect p-Value (η_p^2)	Amplitude Effect p-Value (η_p^2)
Segment onset latencies (s)								
Head	0.40 (0.03)	0.42 (0.04)	0.55 (0.07)	0.37 (0.05)	0.40 (0.07)	0.48 (0.06)	0.003 * (0.22)	<0.001 * (0.07)
Thorax	0.49 (0.05)	0.52 (0.05)	0.55 (0.07)	0.43 (0.05)	0.45 (0.06)	0.53 (0.05)	0.062 (0.03)	<0.001 * (0.55)
Pelvis	0.51 (0.1)	0.53 (0.09)	0.62 (0.11)	0.50 (0.09)	0.55 (0.1)	0.58 (0.09)	0.596 (0.02)	<0.001 * (0.21)
Leading foot	0.68 (0.11)	0.68 (0.10)	0.80 (0.13)	0.55 (0.11)	0.61 (0.13)	0.62 (0.10)	<0.001 * (0.24)	0.002 * (0.15)
Trailing foot	1.12 (0.14)	1.15 (0.16)	1.17 (0.24)	0.68 (0.31)	0.74 (0.24)	0.86 (0.26)	<0.001 * (0.48)	0.225 (0.04)
Peak head yaw velocity (°s^{-1})	103.22 (17.77)	117.27 (18.75)	139.61 (28.63)	123.54 (12.81)	151.54 (25.73)	172.81 (24.86)	<0.001 * (0.19)	<0.001 * (0.33)
Segment angular separations (°)								
Peak head–thorax	10.00 (5.21)	13.60 (7.13)	18.80 (10.04)	20.14 (7.73)	23.80 (8.30)	21.57 (7.00)	<0.001 * (0.21)	0.025 (0.08)
Peak head–pelvis	10.86 (5.77)	15.10 (7.62)	19.63 (11.46)	15.59 (7.62)	23.42 (11.27)	27.63 (12.41)	<0.001 * (0.11)	<0.001 * (0.20)
Total step (n)	2.78 (0.38)	3.48 (0.44)	4.33 (0.49)	1.95 (0.15)	2.75 (0.44)	3.25 (0.41)	<0.001 * (0.58)	<0.001 * (0.77)
Step frequency (Hz)	0.60 (0.30)	1.17 (0.30)	1.53 (0.21)	0.52 (0.24)	1.10 (0.40)	1.34 (0.26)	0.123 (0.02)	0.979 (0.01)
Step duration (s) ✓	1.58 (0.26)	2.09 (0.38)	2.53 (0.66)	0.95 (0.15)	1.91 (0.36)	2.31 (0.28)	<0.001 * (0.22)	<0.001 * (0.79)
Step size (°)	60.81(11.88)	71.21 (10.59)	80.28 (11.62)	73.54 (14.31)	88.55 (24.40)	95.00 (25.95)	<0.001 * (0.17)	<0.001 * (0.27)
Turn speed (°s^{-1}) ✓	58.59 (10.46)	66.54 (11.70)	75.56 (18.31)	96.63 (21.30)	73.92 (17.87)	78.80 (9.73)	<0.001 * (0.23)	<0.001 * (0.07)

✓Denotes a significant interaction ($p < 0.05$). * Denotes significant main effects ($p < 0.05$) from Mixed Model Analysis of Variance.

Table 2. Post hoc comparisons for the main effect of groups and amplitudes in the Mixed Model Analysis of Variance where no interactions between groups and turning amplitudes were observed.

Variables	Groups Compared	Mean Diff (SE)	*p*-Value	CI of Diffs	
				Lower Bound	Upper Bound
Head onset (s)	90° vs. 135°	−0.029 (0.012)	0.046	−0.057	0.001
	90° vs. 180°	−0.133 (0.013)	<0.001 *	−0.164	−0.102
	135° vs. 180°	−0.104 (0.014)	<0.001*	−0.139	−0.069
Thorax onset (s)	90° vs. 135°	−0.029 (0.012)	0.046	−0.058	<0.001
	90° vs. 180°	−0.127 (0.013)	<0.001 *	−0.158	−0.096
	135° vs. 180°	−0.098 (0.013)	<0.001 *	−0.131	−0.065
Pelvis onset (s)	90° vs. 135°	−0.037 (0.022)	0.296	−0.091	0.017
	90° vs. 180°	−0.101 (0.023)	<0.001 *	−0.158	−0.045
	135° vs. 180°	−0.065 (0.023)	0.020	−0.121	−0.008
Leading foot onset (s)	90° vs. 135°	−0.033 (0.026)	0.612	−0.096	0.030
	90° vs. 180°	−0.096 (0.026)	0.001	−0.160	−0.032
	135° vs. 180°	−0.063 (0.027)	0.064	−0.129	0.003
Peak head yaw velocity (°s^{-1})	90° vs. 135°	−21.026 (7.016)	0.013	−38.427	−3.625
	90° vs. 180°	−42.830 (7.339)	<0.001	−61.046	−24.614
	135° vs. 180°	−21.804 (9.544)	0.075	−45.170	1.562
Peak head–pelvis angular separation (°)	90° vs. 135°	−6.043 (2.190)	0.022	−11.409	−0.676
	90° vs. 180°	−10.405 (2.331)	<0.001 *	−16.124	−4.687
	135° vs. 180°	−4.363 (2.549)	0.273	−10.604	1.878
Total step (n)	90° vs. 135°	−0.750 (0.084)	<0.001 *	−0.956	−0.544
	90° vs. 180°	−1.425 (0.085)	<0.001 *	−1.635	−1.215
	135° vs. 180°	−0.675 (0.101)	<0.001 *	−0.921	−0.429
Step size (°)	90° vs. 135°	−12.697 (3.629)	0.002 *	−21.606	−3.789
	90° vs. 180°	−20.465 (3.799)	<0.001 *	−29.799	−11.130
	135° vs. 180°	−7.767 (4.354)	0.235	−18.427	2.892

* Indicates a significant difference (p < 0.05), Diff = Difference, and CI = Confidence Intervals.

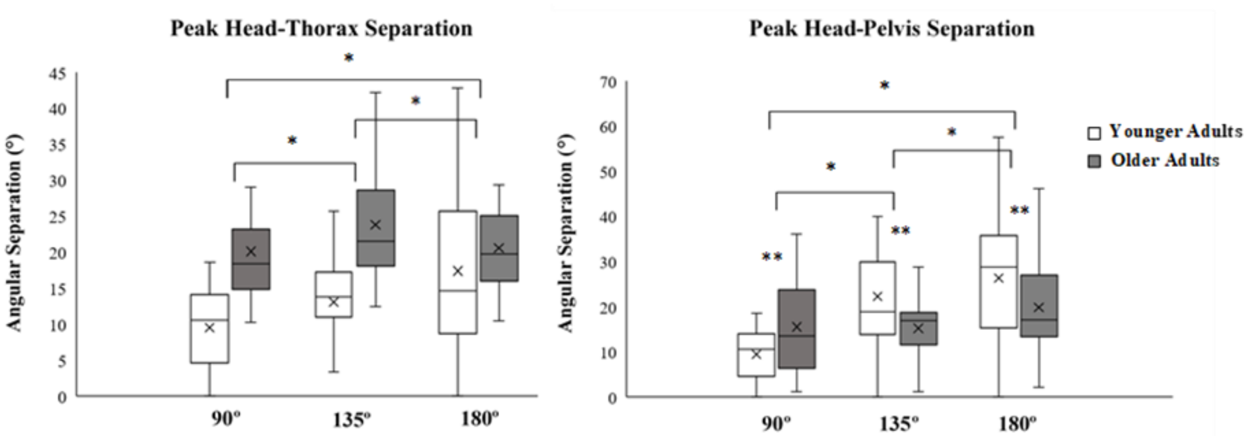

Figure 3. The effects of turning amplitude on mean peak head-segments angular separation in both younger adults and older adult groups. ** Denotes main effects of group from Mixed Model Analysis of Variance. * Denotes main effects of turning amplitude from Mixed Model Analysis of Variance.

3.3. Stepping Characteristics

No significant interactions were observed between direction and amplitude for step size, total step count and step frequency. A significant main effect was seen for group for total step ($F_{(2,40)} = 140.06$, $p < 0.001$, $\eta_p^2 = 0.58$) and step size ($F_{(2,40)} = 21.4$, $p < 0.001$, $\eta_p^2 = 0.17$). The older group showed a significantly greater number of total steps ($p < 0.001$), with differences at 90°, 135° and 180 degrees of 2.78, 3.48 and 4.33 steps, respectively. The older group showed a smaller step size (°) ($p < 0.001$), with differences at 90°, 135° and 180 degrees of 60.81°, 71.21°, and 80.28°, respectively. In addition, significant main effects were seen for turn amplitude for total step ($F_{(2,40)} = 148.35$, $p < 0.001$, $\eta_p^2 = 0.77$) and step size ($F_{(2,40)} = 16.32$, $p < 0.001$, $\eta_p^2 = 0.27$) (Table 1, Table 2 and Figure 4). Post hoc pairwise comparisons showed significant differences in total step and step size for turn amplitude between 90° and 180°, 135° and 180° and 90° and 135° ($p < 0.001$) with both increasing with increasing turn amplitudes (Figure 4). No significant main effects were seen for group or turn amplitude for step frequency.

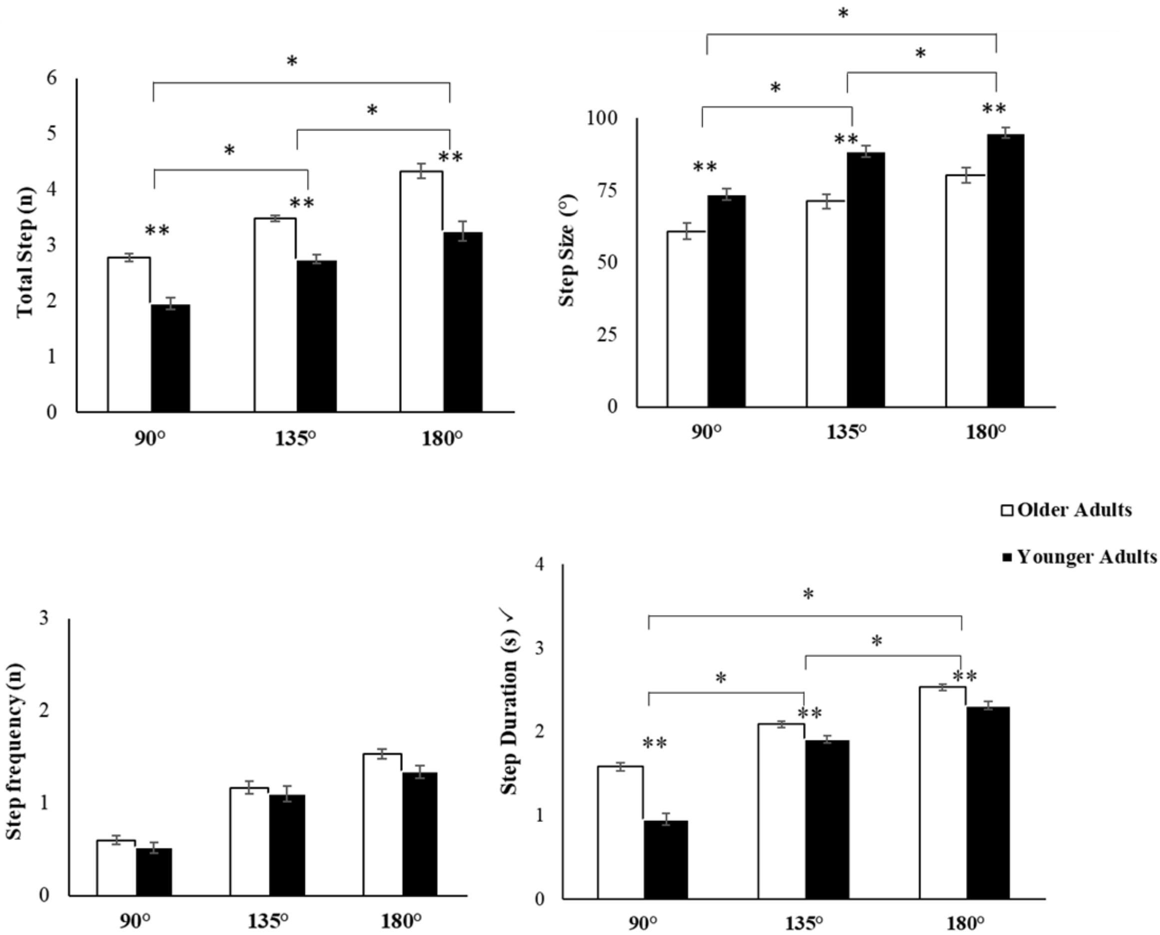

Figure 4. Bar graph showing the effect of group and turn amplitude on stepping characteristics; total number step, step size, step frequency, and step duration. Values are mean ± SEM. ✓Denotes a significant interaction ($p < 0.05$) from Mixed Model Analysis of Variance. * Denotes post hoc pairwise comparisons of turning amplitudes within group from Repeated Measure Analysis of Variance. ** Denotes main effects of group and amplitude from Mixed Model Analysis of Variance.

The analysis of step duration with MM ANOVA demonstrated a significant interaction between groups and turn amplitudes ($p < 0.001$) (Table 1). In addition, RM ANOVA found a main effect of turning amplitude on step duration within the older adults group ($F_{(2,40)} = 23.46$, $p < 0.001$, $\eta_p^2 = 0.41$) and in the younger group ($F_{(2,40)} = 55.67$, $p < 0.001$, $\eta_p^2 = 0.26$) (Table 2). Post hoc pairwise comparisons showed that the step duration increased significantly ($p < 0.001$) with all increases in turning amplitudes in both groups (Table 1 and Figure 4).

3.4. Turning Speed

The MM ANOVA revealed a significant interaction ($p < 0.001$) between groups and turn amplitudes for turning speed (Table 1). Further RM ANOVA tests found a main effect of turning amplitude on the turning speed in the older adults group ($F_{(2,40)} = 11.41$, ($p < 0.0001$), $\eta_p^2 = 0.61$) and the younger adults group ($F_{(2,40)} = 84.97$, $p < 0.0001$, $\eta_p^2 = 0.24$). Post hoc pairwise comparisons showed that the turning speed decreased with an increase in turn amplitude ($p < 0.004$) between 90° and 135°, 90° and 180°, and 135° and 180° in the younger adult group, however, the older adults group only showed differences in turn amplitudes between 90° and 180° (Figure 5).

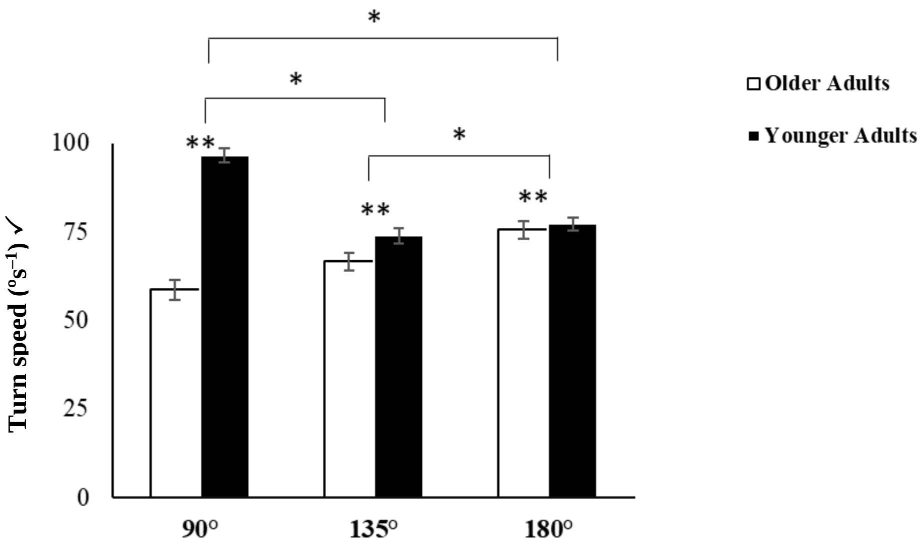

Figure 5. Bar graph showing the effect of group and turn amplitude on turn speed variable. Values are mean ± SEM. ✓Denotes a significant interaction ($p < 0.05$) from Mixed Model Analysis of Variance. * Denotes post hoc pairwise comparisons of turning amplitudes within group from Repeated Measure Analysis of Variance. ** Denotes main effects of group and amplitude from Mixed Model Analysis of Variance.

4. Discussion

The present study aimed to investigate the effect of the amplitude of turning on whole-body coordination during standing turns in healthy older adults in comparison to younger adults and to observe the impact of turning amplitude on whole-body coordination and stepping characteristics. We expected to see systematic changes in the characteristics of turning kinematics and stepping behavior. However, only step duration and turn speed were found to differ significantly between older and younger adults. Other variables appeared to be modulated identically in both groups during the differences in turn amplitudes. It is important to note that the data shows that an increase in turn amplitude had a significant effect as regards segment onset latencies (head, thorax, pelvis and feet), peak segments angular separation, stepping characteristics, and also turning speed in the older adult group in comparison to the younger adult group.

Our study found that the larger turn amplitude significantly affected the order of the reorientation of mean onset latency by delaying the onset of all segments. This delay was consistent between turns to each amplitude, as was segmental onset latency, suggesting that onset latency of segments is regulated by a central nervous system (CNS) regulatory synergy [14,15]. In addition, onset latency of segments in our study consistently shows a top-down sequence which starts with the head and proceeds to the trunk, pelvis, leading foot and trailing foot [12,16–19], which indicates that a motor program for movement may be altered to handle similar motor activities in order to maintain balance and ongoing movement [15,20]. This would also imply that the CNS has a dominant control synergy schema, with the CNS employing the upper body to guide lower-body responses [21]. It stands to reason that the whole-body coordination strategy might have an effect on turning abilities. When the path of movement is disrupted increasing the turning amplitude allows the motor cortex and motor planning more time to absorb sensory information and deliver correction orders to stabilize the body. Turning amplitude only impacts a small portion of the age-phase shift connection, and segment onset latency may not always be the best explanation of turning characteristics in healthy older and younger adults. However, a limitation of this study is that we did not measure eye movements which are described as a trigger of whole-body coordination in both standing and walking turns which could impact on the completion of turning [12,15]. In future work, the characteristics of eye movement need to be evaluated to clarify the effect of changing amplitude during turning.

In this study, we found a significant main effect of turn amplitude ($p < 0.001$) for peak head–thorax angular separations. In addition, significant main effect for both groups ($p < 0.001$) and turning amplitude ($p < 0.001$) were found on peak head–pelvis angular separations. Previous studies found that an en-bloc strategy has been observed in terms of a reduction in head on trunk rotation and a delay in the initiation of body segment rotation during 360° turns in older adults [14,16]. It has been suggested that the en-bloc strategy during turning may be adjusted increasing control and compensation in cases of decreased stability and impaired balance in older adults [3] and individuals with movement disorders such as Parkinson's disease [14]. It is noted that a reduction in angular separation between segments during turning in older adults may represent the normal coordination process associated with smaller turning amplitudes, a by-product of response due to the onset of age-related slowing of movement, self-confidence, balance ability, muscle weakness and individual capacity.

An increase in turn amplitude was associated with an increase in step size, the total number of steps, and step duration. These findings are consistent with Mancini et al. (2016) [22]. These modifications might be attributed to biomechanical factors such as step size, which increased considerably with each increase in the amplitude of turning in both healthy older and younger adults. To verify these results, an analysis of stepping strategies in exercises in which turns were being carried out with full vision and investigating the impact during different turn amplitudes would be necessary. The results of step duration were found to be consistent across an increase in turn amplitude. The explanation is most likely that the central pattern generators in the spinal cord regulate the step variables, especially the temporal step strategies observed during turning. These generators encode the rhythmic pattern employed during walking [23,24]. In addition, placement of the step strategy during pre-planned turns may be a deliberate process or reactive and depends on the individual's visual perception of the environment [15,19]. Changes in turn amplitude appear to be formulated and carried out during pre-planned turns by modifying the temporal stepping characteristics. Furthermore, changes in the amplitude of the turns appear to be mediated by adjusting the size of the steps. Given that stepping frequency is not affected by turn amplitude, our proposal is that changes in step frequency can be achieved by increasing step size during turning.

Another explanation is that when head–trunk separation decreases, stepping characteristics change to preserve balance and stability throughout the turn [18,23,25]. Our findings support the idea that reducing head-on-trunk rotation has an effect on the stepping characteristics which are important for the essential capacity to maintain postural balance at various turn amplitudes [25,26]. Previous studies suggest that a narrow step width might be the result of the generation of insufficient force to accelerate the center of mass (COM) in the direction and amplitude of the turn, resulting in a destabilizing impact and adaptation in step strategy [23,24,26].

Regardless of variations in turn amplitude, we found that turn speed in the older adults group remained constant. In contrast, in the younger adult group, the turn speed decreased as the intended turn amplitude increased. A previous study found that when the radius of the curve increases, the velocity of the COM during steering falls systematically in older adults. However, segmental velocity appears to increase with higher turn amplitude in both healthy older and younger adults while the radius is constant as a standing turn [27]. This is likely to be due to the standing turns requiring the COM need to remain balanced within a rotation while a sufficient base of support is needed and is controlled via stepping mechanisms and postural demands more significantly in older adults in comparison to younger adults. Other characteristics, including muscle and brain activity, should be investigated in future research into turning kinematics in order to expand our understanding of turning strategies.

5. Conclusions

Whole-body coordination and stepping characteristics during different turn amplitudes are preserved by step duration and turning speed. However, in both groups, young and older adults, an increase in turn amplitude was associated with changes in turning kinematics such as segment onset latency, peak segment angular separation, stepping characteristics, and also turning speeds. Furthermore, changes in turn amplitudes had significant effects in the older adult group compared to the younger adult group. Variations in turning amplitude altered whole-body coordination and stepping characteristics, indicating a potential interaction between the area of the base of support and the body segment rotation during standing turns. These results indicate that turning amplitude is a critical factor in turning and is related to the regulation of the turning strategy, particularly for the maintenance of balance and stepping movement control. Therefore, this factor may be beneficial for the identification of individuals who are increasingly at risk of falling while changing direction, and it may subsequently be used to advise and educate more effective exercise in the healthy elderly or those in frail populations, particularly with regard to turning to enhance quality of life and prevent falling and the risk of disability.

Author Contributions: Conceptualization, F.K. and J.R.; methodology, F.K., J.R. and M.H.; writing—original draft preparation, F.K., M.H. and J.R.; writing—review and editing, F.K., M.H. and J.R.; supervision, J.R. and M.H.; project administration, F.K. and J.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research project was supported by the Faculty of Physical Therapy, Mahidol University (No. IO 865392003000).

Institutional Review Board Statement: This study was conducted with the approval of the institutional ethics committee of the Mahidol University (COA No. MU-CIRB 2021/136.0806) and complied with the ethical standards laid down in the guidelines of the Declaration of Helsinki.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We would like to express our gratitude to Damrongsak Ruaysungnoen and United BMEC (Bangkok, Thailand) Co., Ltd. for their support of XSENS, and Chayakorn Khantikosol, Kwanrudee Kamrueng and Panisa Lochanajaroenporn for their help of data collection. We would also like to thank all participants in the experiments and the members of the Faculty of Physical Therapy, Mahidol University.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Patla, A.E.; Adkin, A.; Ballard, T. Online steering: Coordination and control of body center of mass, head and body reorientation. *Exp. Brain Res.* **1999**, *129*, 629–634. [CrossRef] [PubMed]
2. Thigpen, M.T.; Light, K.E.; Creel, G.L.; Flynn, S.M. Turning difficulty characteristics of adults aged 65 years or older. *Phys. Ther.* **2000**, *80*, 1174–1187. [CrossRef] [PubMed]
3. Wright, R.L.; Peters, D.M.; Robinson, P.D.; Sitch, A.J.; Watt, T.N.; Hollands, M.A. Differences in axial segment reorientation during standing turns predict multiple falls in older adults. *Gait Posture* **2012**, *36*, 541–545. [CrossRef] [PubMed]
4. Welch, S.A.; Ward, R.E.; Kurlinski, L.A.; Kiely, D.K.; Goldstein, R.; VanSwearingen, J.; Brach, J.S.; Bean, J.F. Straight and curved path walking among older adults in primary care: Associations with fall-related outcomes. *PM R* **2016**, *8*, 754–760. [CrossRef]
5. Masui, T.; Hasegawa, Y.; Matsuyama, Y.; Sakano, S.; Kawasaki, M.; Suzuki, S. Gender differences in platform measures of balance in rural community-dwelling elders. *Arch. Gerontol. Geriatr.* **2005**, *41*, 201–209. [CrossRef]
6. Kasović, M.; Štefan, L.; Štefan, A. Normative Data for Gait Speed and Height Norm Speed in $\geq$ 60-Year-Old Men and Women. *Clin. Interv. Aging* **2022**, *16*, 225–230. [CrossRef]
7. Khobkhun, F.; Hollands, M.; Richards, J. The effect of different turn speeds on whole-body coordination in younger and older healthy adults. *Sensors* **2021**, *21*, 2827. [CrossRef]
8. Zanelli, G.; Cappa, P.; Petrarca, M.; Berthoz, A. Vestibular and proprioceptive estimation of imposed rotation and spatial updating in standing subjects. *Gait Posture* **2011**, *33*, 582–587. [CrossRef]
9. Pham, M.H.; Elshehabi, M.; Haertner, L.; Heger, T.; Hobert, M.A.; Faber, G.S.; Salkovic, D.; Ferreira, J.J.; Berg, D.; Sanchez-Ferro, Á.; et al. Algorithm for turning detection and analysis validated under home-like conditions in patients with Parkinson's disease and older adults using a 6 degree-of-freedom inertial measurement unit at the lower back. *Front. Neurol.* **2017**, *8*, 135–143. [CrossRef]
10. Renggli, D.; Graf, C.; Tachatos, N.; Singh, N.; Meboldt, M.; Taylor, W.R.; Stieglitz, L.; Schmid Daners, M. Wearable inertial measurement units for assessing gait in real-world environments. *Front. Physiol.* **2020**, *11*, 90–103. [CrossRef]
11. Muangpaisan, W.; Assantachai, P.; Sitthichai, K.; Richardson, K.; Brayne, C. The Distribution of Thai Mental State Examination Scores among non-demented elderly in Suburban Bangkok Metropolitan and associated factors. *J. Med. Assoc. Thai* **2015**, *98*, 916–924.
12. Robins, R.K.; Hollands, M.A. The effects of constraining vision and eye movements on whole-body coordination during standing turns. *Exp. Brain Res.* **2017**, *235*, 3593–3603. [CrossRef]
13. Khobkhun, F.; Hollands, M.A.; Richards, J.; Ajjimaporn, A. Can we accurately measure axial segment coordination during turning using Inertial Measurement Units (IMUs)? *Sensors* **2020**, *20*, 2518. [CrossRef] [PubMed]
14. Ashburn, A.; Kampshoff, C.; Burnett, M.; Stack, E.; Pickering, R.M.; Verheyden, G. Sequence and onset of whole-body coordination when turning in response to a visual trigger: Comparing people with Parkinson's disease and healthy adults. *Gait Posture* **2014**, *39*, 278–283. [CrossRef] [PubMed]
15. Reed-Jones, R.J.; Hollands, M.A.; Reed-Jones, J.G.; Vallis, L.A. Visually evoked whole-body turning responses during stepping in place in a virtual environment. *Gait Posture* **2009**, *30*, 317–321. [CrossRef] [PubMed]
16. Akram, S.B.; Frank, J.S.; Fraser, J. Coordination of segments reorientation during on-the-spot turns in healthy older adults in eyes-open and eyes-closed conditions. *Gait Posture* **2010**, *32*, 632–636. [CrossRef]
17. Hase, K.; Stein, R. Turning strategies during human walking. *J. Neurophysiol.* **1999**, *81*, 2914–2922. [CrossRef]
18. He, C.; Xu, R.; Zhao, M.; Guo, Y.; Jiang, S.; He, F.; Ming, D. Dynamic stability and spatiotemporal parameters during turning in healthy young adults. *Biomed. Eng. Online* **2018**, *17*, 127–132. [CrossRef]
19. Hollands, M.A.; Ziavra, N.V.; Bronstein, A.M. A new paradigm to investigate the roles of head and eye movements in the coordination of whole-body movements. *Exp. Brain Res.* **2004**, *154*, 261–266. [CrossRef]
20. Reed-Jones, R.J.; Reed-Jones, J.G.; Vallis, L.A.; Hollands, M.A. The effects of constraining eye movements on visually evoked steering responses during walking in a virtual environment. *Exp. Brain Res.* **2009**, *197*, 357–367. [CrossRef]
21. McGibbon, C.A.; Krebs, D.E. Age-related changes in lower trunk coordination and energy transfer during gait. *J. Neurophysiol.* **2001**, *85*, 1923–1931. [CrossRef] [PubMed]
22. Mancini, M.; Schlueter, H.; El-Gohary, M.; Mattek, N.; Duncan, C.; Kaye, J.; Horak, F.B. Continuous monitoring of turning mobility and its association to falls and cognitive function: A pilot study. *J. Gerontol. A Biol. Sci. Med. Sci.* **2016**, *71*, 1102–1108. [CrossRef] [PubMed]
23. Fuller, J.R.; Adkin, A.L.; Vallis, L.A. Strategies used by older adults to change travel direction. *Gait Posture* **2007**, *25*, 393–400. [CrossRef]
24. Akram, S.B.; Frank, J.S.; Chenouri, S. Turning behavior in healthy older adults: Is there a preference for step versus spin turns? *Gait Posture* **2010**, *31*, 23–26. [CrossRef]
25. Chapman, G.J.; Hollands, M.A. Evidence that older adult fallers prioritise the planning of future stepping actions over the accurate execution of ongoing steps during complex locomotor tasks. *Gait Posture* **2007**, *26*, 59–67. [CrossRef] [PubMed]
26. Forsell, C.; Conradsson, D.; Paquette, C.; Franzén, E. Reducing gait speed affects axial coordination of walking turns. *Gait Posture* **2017**, *54*, 71–75. [CrossRef] [PubMed]
27. Vieilledent, S.; Kerlirzin, Y.; Dalbera, S.; Berthoz, A. Relationship between velocity and curvature of a human locomotor trajectory. *Neurosci. Lett.* **2001**, *305*, 65–69. [CrossRef]