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Spatiotemporal parameters during turning gait maneuvers of different amplitudes in young and elderly healthy adults: A descriptive and comparative study

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ABSTRACT

Background: Turning during walking adds complexity to gait and has been little investigated until now.

Research question

What are the differences in spatiotemporal parameters between young and elderly healthy adults performing quarter-turns (90°), half-turns (180°) and full-turns (360°)?

Methods: The spatiotemporal parameters of 10 young and 10 elderly adults were recorded in a laboratory while turning at 90°, 180° and 360°. Two-way mixed ANOVA were performed to determine the effect of age and turning amplitude.

Results: Elderly were slower and needed more steps and time to perform turns of larger amplitude than young adults. Cadence did not differ across age or across turning amplitude. Generally, in the elderly, the spatial parameters were smaller and the temporal parameters enhancing stability (i.e., double-support phase and stance/cycle ratio) were larger, especially for turns of larger amplitudes. In elderly adults, the variability of some spatial parameters was decreased, whereas the variability of some temporal parameters was increased. Stride width of the external leg showed the most substantial difference between groups. Most parameters differed between turning at 90° and turning at larger amplitudes (180°, 360°).

Significance

This study extends the characterization of turning biomechanics with respect to ageing. It also suggested paying particular attention to the turning amplitude. Finally, the age-related differences may pave the way for new selective rehabilitation protocols in the elderly.

1. Introduction

Task of higher complexity increases the attentional demand to control posture and locomotion [1]. Therefore, more challenging tasks might show higher sensitivity when comparing the gait pattern of different groups. Studying turning maneuvers could help to better understand walking biomechanics in general, as well as to improve clinical evaluation and treatment. Analyzing turning is furthermore of interest because all kind of daily activities involve turning maneuvers and because gait impairment may become aggravated during turning [2]. For example, falls are more frequent during turning in the elderly [3]. Unfortunately, so far, research focused mainly on straight-line walking and there remain many unknowns regarding turning biomechanics.

In particular, there is a need to improve our understanding of the effect of age in the turning biomechanics of healthy individuals. A prior work has shown that healthy elderly prefer spin turns on the internal leg, whereas younger adults prefer step turns [4]. Two other studies comparing the turning patterns of elderly and young adults reported that elderly do not use a pivot shift strategy, are slower, need more steps, take more time, and have shorter step length and longer step duration

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[5,6]. While these prior studies showed that spatiotemporal turning biomechanics differ with ageing, additional research is necessary to get a comprehensive description of the effect of age. There is particularly little evidence concerning temporal parameters during turning.

Since turning amplitude has been reported to affect the turning strategy [3], a comprehensive description of the age effect requires the analysis of diverse turning amplitudes. Additionally, because the variability of the spatiotemporal parameters has been shown to complement the information provided by the parameters themselves in the understanding and detection of gait alterations [7], there is an interest to assess the age and turning amplitude effects on the variability of the spatiotemporal parameters as well. Gait variability was originally considered to represent physiological or instrumentational noise. However, in the last decade gait parameters variability demonstrated even better sensitivity to discriminate the healthy ageing and pathological gait pattern than standard spatiotemporal parameters [7].

This study aimed to provide a comprehensive description and comparison of the spatiotemporal parameters and of their variabilities in young and elderly healthy adults performing quarter-turns (90°), half-turns (180°) and full-turns (360°).

2. Methods

2.1. Participants

Young healthy adults between 20 and 30 years of age, and elderly healthy adults between 60 and 85 years of age were recruited. Individuals with walking disabilities or comorbidities affecting gait and locomotion; suffering from cardiac, respiratory, metabolic, neurologic, muscular or skeletal pathologies, were excluded from the study. Obese volunteers (BMI>30 kg/m^2) were also excluded. In total, 20 persons were included: 10 young adults (5 males, 23 ± 1 years old, BMI 21.3 ± 2.2 kg/m2) and 10 elderly adults (4 males, 72 ± 5 years old, BMI 26.4 ± 6.4 kg/m2). The sample size of 10 participants per group was defined based on prior research on spatiotemporal parameters with comparable descriptive and exploratory objectives [8]. Participants gave their written informed consent before taking part in the study, which was approved by the local ethics committee.

2.2. Procedure

Participants were equipped with reflective markers on both feet and on the pelvis [9]. Foot markers were placed bilaterally to the posterior side of the calcaneus and the second metatarsal heads. Pelvis markers were placed to both anterior superior and posterior superior iliac spines. Thereafter, participants were asked to perform practice trials and thereafter the recorded turning trials, barefoot, in a laboratory equipped with a motion capture system recording at sampling rate of 120 Hz (Vicon, Oxford, UK).

Participants were instructed to walk straight for 5 m, perform either a quarter-turn, half-turn or a full-turn around a 153 cm vertical rod, and then continued walking straight for at least 3 m until they reached a fixed point in the room, specific to the turn performed (Fig. 1). No specific path was imposed to the participant, and no specific instruction was given on doing either a sharp or a smooth turn. Three turning amplitudes were recorded: quarter-turn (90°), half-turn (180°) and full-turn (360°). The order of the turning amplitudes and the turning direction (left or right) were randomized by simple global randomization. For each participant, nine trials at self-selected normal walking speed were recorded per turning condition. The participants did not need breaks and did not complain about fatigue. We compared the first and last trial in order to be sure that fatigue had no effect on the gait pattern (Supplementary 2).

2.3. Data processing

Heel-strike and toe-off events were detected using foot marker trajectories following the recommendations of Ulrich and colleagues [9]. Specifically, the algorithm proposed by O'Connor et al. [10] was used for heel-strike detection and the algorithm proposed by Zeni et al. [11] for toe-off detection. The turning period was defined as the portion of the trials with an angular velocity of the pelvis exceeding 30°/s [12]. Extending from this definition, spatiotemporal parameters were analyzed between the last toe-off before the onset of the turning period until the first heel-strike after the end of the turning period. The following spatiotemporal parameters were measured: 1) for the entire turn: speed, duration, number of steps and cadence (duration/number of steps), 2) for the external and internal legs during each cycle: stride length, stride width, step length, gait cycle duration, stance duration, stance/cycle ratio and initial double-support duration (Fig. 2) [13,14].

2.4. Statistical analysis

For each participant, the measures were pooled over the nine trials of each turning amplitude. Then, the mean and the within-subject standard deviation (SD), as an estimate of variability [15,16], were calculated for each pooled dataset, resulting in two data points (average value and variability) for each parameter, turning amplitude and participant. We chose SD rather than the coefficient of variation (CV) because CV becomes problematic when numerical values are near zero (e. g. stride width).

To determine if age and/or turning amplitude had an effect on the spatiotemporal parameters and on their variability, statistical models with a between-subject group factor (young or elderly adults) and a within-subject turning amplitude factor (90°, 180° or 360°) were built separately for the average and variability values of each parameter. This

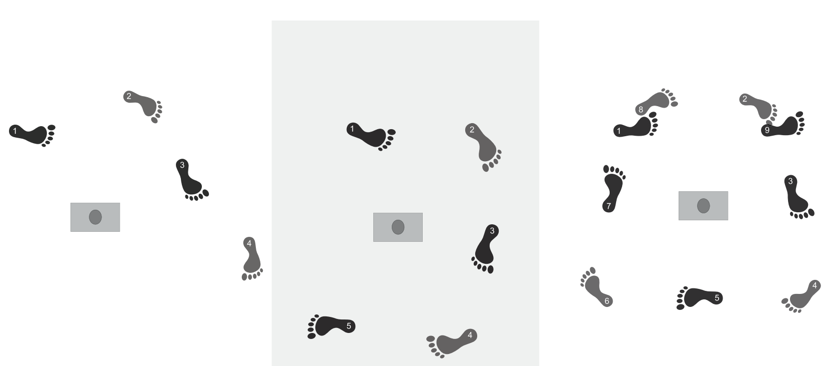

Fig. 1. Illustration of the experimental procedure, with turns of 90° (a), 180° (b) and 360° (c). The colors indicate internal versus external foot placement. The numbers indicate the order of the foot placements and start at turning initiation.

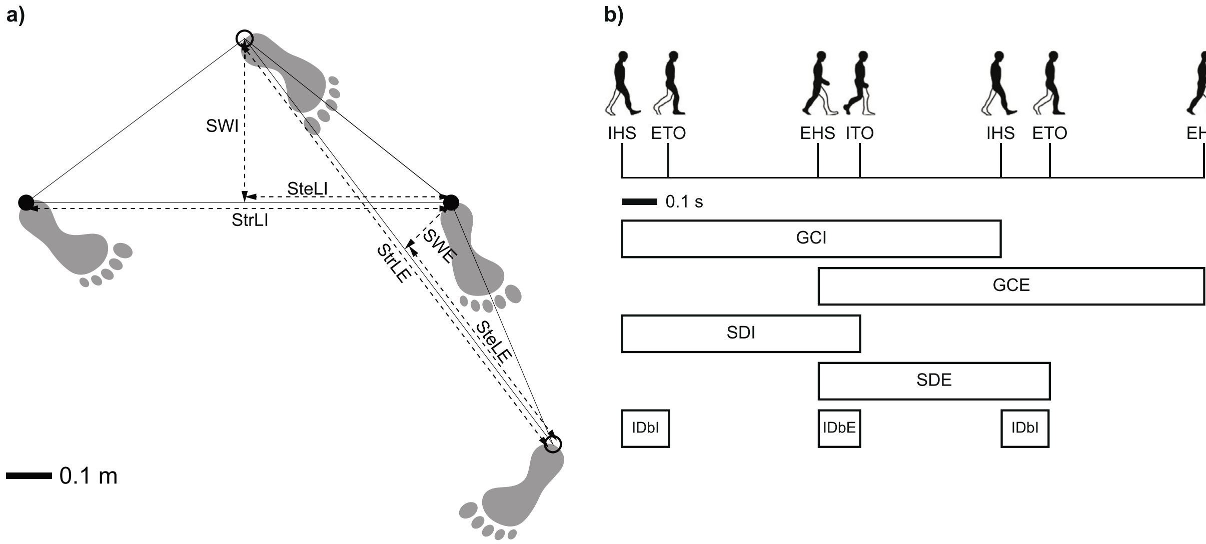

Fig. 2. a) Spatial gait parameters: stride length of internal leg (StrLI); stride length of external leg (StrLE); step length of internal leg (SteLI); step length of external leg (SteLE); stride width of internal leg (SWI); stride width of external leg (SWE). b) Temporal gait parameters: internal heel-strike event (IHS); external toe-off event (ETO); external heel-strike event (EHS); internal toe-off event (ITO); gait cycle duration of internal leg (GCI); gait cycle duration of external leg (GCE); stance duration of internal leg (SDI); stance duration of external leg (SDE); initial double-support duration of internal leg (IDbI); initial double-support duration of external leg (IDbE).

was done by computing 2 × 3 two-way mixed ANOVA. Generalized eta squared η^2_G was computed as an effect size estimate. QQ-plots were used to test for normality, Levene's tests to test for the homogeneity of variances, Mauchly's tests to test for sphericity, and box's M tests to test for the homogeneity of the covariance matrices. Because participants were randomly selected, independence was assumed. When violation of sphericity occurred, the Greenhouse–Geisser corrected p-value was reported. Failure to fulfil parametric assumptions led to the use of the Aligned Rank Transform (ART) [17] before running the two-way mixed ANOVA.

Post-hoc analyses to identify the statistically significant differences between groups and turning amplitudes were performed with paired and unpaired t-tests or with Wilcoxon Rank-Sum and Signed-Rank tests. Cross-factor pairwise comparisons were calculated using Wilcoxon Rank-Sum and Signed-Rank Tests, when the interaction between the turning amplitude and age factors was statistically significant. When necessary, the Holm-sequential Bonferroni correction was used. In case of non-parametric distributions, means and 95 % confidence intervals were obtained by bootstrapping. Statistical analyses were performed in RStudio (v 1.2.1335, RStudio, Inc.) and Matlab (R2019a, the Mathworks Inc., Natick, USA). For all tests, significance level was set a priori at $p = 0.05$.

3. Results

For the sake of consistency, only statistically significant differences are presented in this section.

3.1. Spatiotemporal parameters

Elderly adults walked statistically significantly slower than young adults during all turning amplitudes ($p < 0.025$). Furthermore, both groups decreased their speed consistently with larger turning amplitudes ($p < 0.001$). Turning duration differed between groups at 180° ($p = 0.025$) and 360° ($p < 0.001$). The total number of steps differed at 360° ($p < 0.001$). Neither the age nor the turning amplitude affected the cadence (ANOVA age $p = 0.6$, $\eta^2_G = 0.01$; amplitude $p = 0.14$, $\eta^2_G = 0.005$; interaction $p = 0.77$, $\eta^2_G = 0.0003$).

For 16 of the 18 stride length, step length and stride width measures, the elderly participants had significantly shorter measures compared to the younger adults ($p < 0.028$). Regarding the effect of turning amplitude, for both groups, stride length and step length of the internal leg decreased from 90° to 180° and 360° ($p < 0.001$), whereas for the external leg they decreased only between 90° and 180° ($p < 0.001$). Young adults increased their external stride width with larger turning amplitudes ($p < 0.03$).

Initial double-support duration (IDSD) and stance/cycle ratio were significantly higher in elderly as compared to young participants (ANOVA $p < 0.03$, $\eta^2_G > 0.21$). For both groups, stance duration (ANOVA $p < 0.005$, $\eta^2_G > 0.01$) differed with respect to the turning amplitude. For the internal leg of both groups, stance duration increased from 90° to 180° ($p < 0.001$), but did not increase further from 180° to 360° ($p = 0.51$). For the external leg of both groups, stance duration increased from 90° to 180° ($p = 0.006$) and decreased from 180° to 360° ($p = 0.01$). Turning amplitude had similar effects on the IDSD of the internal and external legs (90° vs 180°internal leg ($p < 0.001$), external leg ($p = 0.003$); 180° vs 360° internal leg ($p = 0.24$), external leg ($p = 0.15$)). Stance/cycle ratio of the internal leg increased with larger turning amplitudes in the young group (90° vs 180° ($p = 0.002$); 90° vs 360° ($p < 0.001$)) and in the elderly group (90° vs 180° ($p < 0.001$); 90° vs 360° ($p < 0.001$)). Furthermore, while the stance/cycle ratio of the internal leg increased consistently with larger turning amplitudes in young adults (90° vs 180° ($p = 0.002$); 180° vs 360° ($p = 0.002$)), in elderly adults, it increased only from 90° to 180° ($p < 0.001$).

These results are summarized in Table 1 and Figs. 3 & 4.

3.2. Spatiotemporal parameters variability

Speed's variability statistically significantly decreased between 360° and 90° turns ($p = 0.025$).

The variability of the external leg stride width was lower in the elderly compared to the young adults for all turning amplitudes ($p < 0.003$). Except for this comparison and the step length variability of the internal leg –which showed no differences between groups (ANOVA $p = 0.45$, $\eta^2_G = 0.01$)– the variability of all spatial parameters was lower in the elderly either for 180° or 360° turns ($p < 0.03$). Differences in variability were particularly significant at 180° for the internal leg ($p < 0.001$), and at 360° for the external leg ($p < 0.03$).

In young adults, the variability of stride length for the internal leg increased from 90° to 180° ($p < 0.001$), and it decreased from 180° to

Table 1
Spatiotemporal parameters.

Parameter	Young Mean (95%CI) 90°	Young 180°	Young 360°	Elderly Mean (95%CI) 90°	Elderly 180°	Elderly 360°	Differences with respect to: Age	Differences with respect to: Turning amplitude
Speed (m/s)	1.13 (1.07; 1.20)	0.995 (0.919; 1.08)	0.891 (0.809; 0.978)	0.954 (0.883; 1.01)	0.808 (0.744; 0.873)	0.754 (0.692; 0.815)	90°: E<Y^{b} 180°: E<Y^{b} 360°: E<Y^{a}	Both: 90>180^{c}; 90>360^{c}; 180>360^{c}
Turning duration (s)	1.47 (1.41; 1.54)	2.23 (2.14; 2.30)	3.59 (3.43; 3.72)	1.47 (1.37; 1.56)	2.44 (2.30; 2.57)	4.44 (4.09; 4.77)	90°: ns 180°: E>Y^{a} 360°: E>Y^{c}	Y: 90<180^{c}; 90<360^{c}; 180<360^{c} E: 90<180^{c}; 90<360^{c}; 180<360^{c}
Number of steps (-) #	3.76 (3.64; 3.88)	5.13 (4.98; 5.27)	7.73 (7.30; 8.07)	3.71 (3.50; 3.91)	5.41 (5.22; 5.62)	9.04 (8.59; 9.47)	90°: ns 180°: ns 360°: E>Y^{c}	Y: 90<180^{a}; 90<360^{a}; 180<360^{a} E: 90<180^{a}; 90<360^{b}; 180<360^{a}
Cadence (steps/min)	113 (109; 117)	111 (107; 116)	113 (109; 116)	111 (105; 118)	109 (103; 117)	110 (103; 118)	ns	ns
Stride length: internal leg (m)	1.069 (1.016; 1.124)	0.930 (0.884; 0.975)	0.837 (0.793; 0.879)	0.884 (0.828; 0.942)	0.721 (0.662; 0.782)	0.702 (0.642; 0.764)	90°: E<Y^{c} 180°: E<Y^{c} 360°: E<Y^{b}	Both: 90>180^{c}; 90>360^{c}; 180>360^{b}
Stride length: external leg (m)	1.249 (1.209; 1.290)	1.115 (1.069; 1.163)	1.069 (1.027; 1.109)	1.052 (0.996; 1.117)	0.939 (0.879; 1.004)	0.948 (0.886; 1.012)	90°: E<Y^{c} 180°: E<Y^{c} 360°: E<Y^{b}	Both: 90>180^{c}; 90>360^{c}; ns
Step length: internal leg (m)	0.535 (0.504; 0.563)	0.452 (0.417; 0.484)	0.403 (0.377; 0.426)	0.425 (0.392; 0.452)	0.333 (0.299; 0.360)	0.311 (0.286; 0.337)	90°: E<Y^{c} 180°: E<Y^{c} 360°: E<Y^{c}	Both: 90>180^{c}; 90>360^{c}; 180>360^{c}
Step length: external leg (m) #	0.642 (0.625; 0.659)	0.574 (0.547; 0.599)	0.552 (0.527; 0.578)	0.554 (0.517; 0.592)	0.500 (0.464; 0.538)	0.507 (0.466; 0.554)	90°: E<Y^{a} 180°: E<Y^{a} 360°: ns	Both: 90>180^{c}; 90>360^{c}; ns
Stride width: internal leg (m)	0.359 (0.338; 0.381)	0.359 (0.342; 0.377)	0.378 (0.358; 0.400)	0.339 (0.311; 0.367)	0.327 (0.309; 0.343)	0.330 (0.310; 0.352)	90°: ns 180°: E<Y^{a} 360°: E<Y^{b}	ns
Stride width: external leg (m)	-.0738 (-.0890; -.0601)	-.138 (-.155; -.119)	-.162 (-.186; -.137)	-.0246 (-.0581; .00415)	-.0341 (-.0609; -.00306)	-.0391 (-.0691; -.00991)	90°: E>Y^{a} 180°: E>Y^{c} 360°: E>Y^{c}	Y: 90>180^{c}; 90>360^{c}; 180>360^{a}
Gait cycle duration: internal leg (s)	1.06 (1.02; 1.09)	1.07 (1.03; 1.11)	1.07 (1.03; 1.10)	1.09 (1.03; 1.15)	1.11 (1.04; 1.17)	1.11 (1.02; 1.17)	ns	ns
Gait cycle duration: external leg (s)	1.07 (1.03; 1.11)	1.09 (1.04; 1.13)	1.07 (1.04; 1.11)	1.08 (1.03; 1.14)	1.11 (1.05; 1.17)	1.11 (1.03; 1.17)	ns	ns
Stance duration: internal leg (s)	0.658 (0.634; 0.681)	0.673 (0.641; 0.701)	0.669 (0.644; 0.694)	0.690 (0.647; 0.737)	0.720 (0.671; 0.766)	0.719 (0.671; 0.767)	ns	Both: 90<180^{c}; 90<360^{b}; ns
Stance duration: external leg (s)	0.645 (0.618; 0.665)	0.654 (0.626; 0.680)	0.639 (0.616; 0.662)	0.672 (0.626; 0.713)	0.692 (0.639; 0.742)	0.684 (0.629; 0.731)	ns	Both: 90<180^{b}; ns; 180>360^{b}
Initial double-support duration: internal leg (s)	0.121 (0.110; 0.131)	0.131 (0.117; 0.143)	0.127 (0.115; 0.137)	0.141 (0.127; 0.157)	0.158 (0.140; 0.176)	0.156 (0.140; 0.171)	90°: ns 180°: E>Y^{a} 360°: E>Y^{b}	Both: 90<180^{c}; 90<360^{b}; ns
Initial double-support duration: external leg (s)#	0.110 (0.101; 0.117)	0.115 (0.106; 0.123)	0.113 (0.106; 0.118)	0.132 (0.115; 0.149)	0.148 (0.127; 0.168)	0.144 (0.126; 0.165)	90°: ns 180°: E>Y^{a} 360°: E>Y^{a}	Both: 90<180^{b}; 90<360^{b}; ns
Stance/cycle ratio: internal leg (%)	60.38 (59.84; 60.91)	61.76 (61.06; 62.51)	62.47 (61.72; 63.19)	62.01 (61.08; 63.00)	64.49 (63.59; 65.40)	65.10 (64.20; 65.95)	90°: E>Y^{a} 180°: E>Y^{c} 360°: E>Y^{c}	Y: 90<180^{b}; 90<360^{c}; 180<360^{b} E: 90<180^{c}; 90<360^{c}; ns
Stance/cycle ratio: external leg (%)	59.38 (58.45; 60.25)	59.60 (58.76; 60.43)	59.31 (58.46; 60.11)	60.99 (60.12; 61.88)	61.48 (60.44; 62.54)	61.34 (60.17; 62.44)	90°: E>Y^{a} 180°: E>Y^{a} 360°: E>Y^{a}	ns

Statistically significant ANOVA results ($p < 0.05$) are highlighted in green when there was an effect of age or turning amplitude, and in brown when there was an age x amplitude interaction.

Only statistically significant differences in post-hoc analyses are reported ([a]: $p < 0.05$, [b]: $p < 0.01$, [c]: $p < 0.001$).
[#]Non-parametric tests (ANOVA on a rank transformed scale)
Y: young adults, E: elderly adults.
90°: quarter-turn, 180°: half-turn, 360°: full-turn.

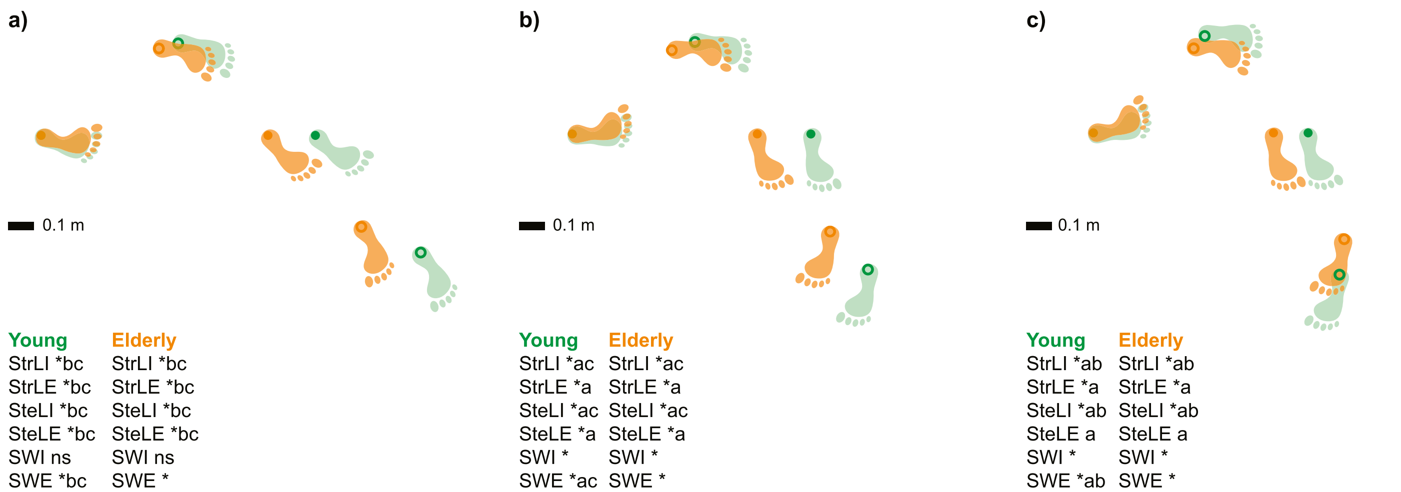

Fig. 3. Spatial parameter differences between young and elderly adults during turning at a) 90° b) 180 °c) 360°. Measurements based on averaged parameters, using the calcaneus marker as reference. Significant differences between young and elderly are marked with stars. Significant differences between the given amplitude and 90°, 180°, 360° are marked with a, b, c, respectively. Non-significant (ns). Stride-length of internal leg (StrLI); Stride-length of external leg (StrLE); Step-length of internal leg (SteLI); Step-length of external leg (SteLE); Stride-width of internal leg (SWI); Stride-width of external leg (SWE).

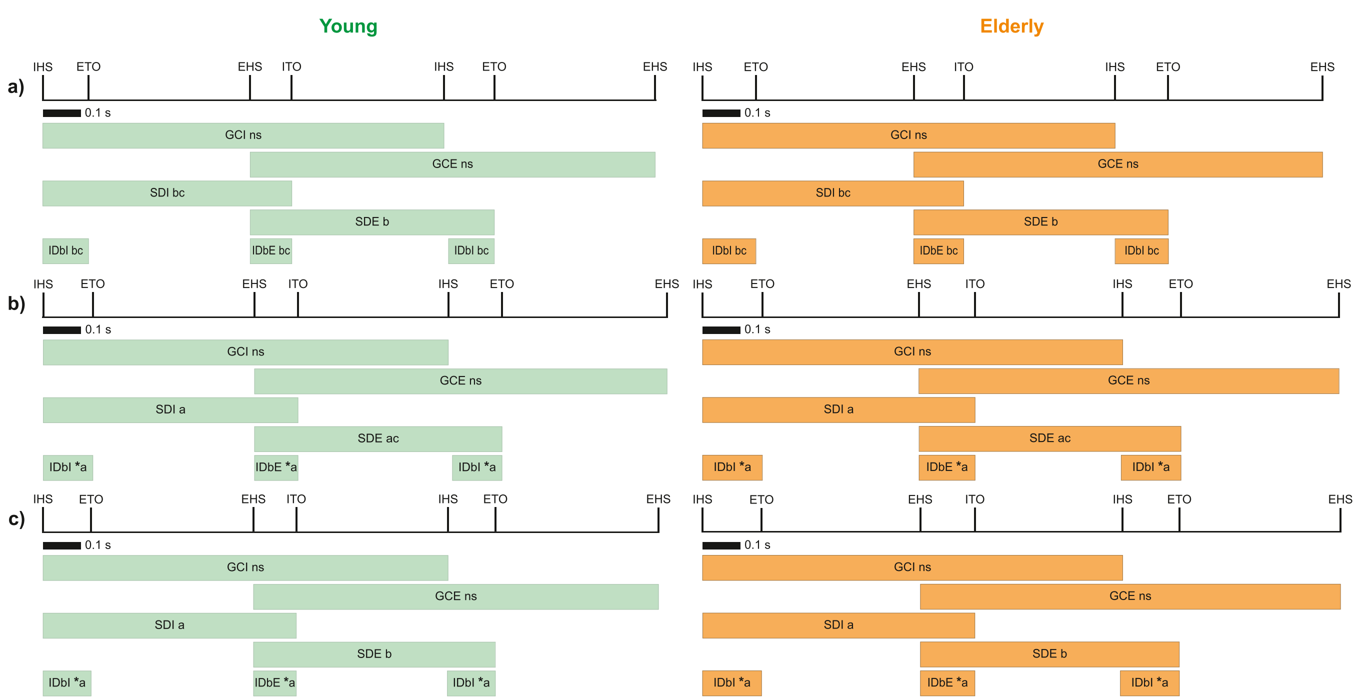

Fig. 4. Temporal parameter differences between young and elderly adults turning at a) 90° b) 180 °c) 360°. The length corresponds to the duration in seconds. Significant differences between young and elderly are marked with stars. Significant differences between the given amplitude and 90°, 180°, 360° are marked with a, b, c, respectively. Non-significant (ns). Internal heel-strike (IHS); External toe-off (ETO); External heel-strike (EHS); Internal toe-off (ITO); Gait cycle duration of internal leg (GCI); Gait cycle duration of external leg (GCE); Stance duration of internal leg (SDI); Stance duration of external leg (SDE); Initial double-support duration of internal leg (IDbI); Initial double-support duration of external leg (IDbE).

360° ($p = 0.007$) turning amplitude. In elderly adults, it increased from 90° to 180° ($p < 0.009$) and stayed constant from 180° to 360° ($p = 0.68$). In young adults, the external leg stride length variability increased for larger turning amplitudes (180° and 360° $p < 0.02$).

The variability of the external leg gait cycle duration, internal leg initial double support duration and internal leg stance ratio was higher in elderly adults for 180° or 360° ($p < 0.04$). The variability of the other temporal parameters did not show any difference among age groups (ANOVA $p > 0.08$, $\eta^2_G < 0.13$).

These results are summarized in Table 2.

Table 2
Variability of the spatiotemporal parameters.

Parameter SD	Young Mean (95%CI) 90°	180°	360°	Elderly Mean (95%CI) 90°	180°	360°	Differences with respect to: Age	Turning amplitude
Speed (m/s)	0.0441 (0.0340; 0.0546)	0.044 (0.035; 0.054)	0.035 (0.029; 0.039)	0.048 (0.041; 0.054)	0.037 (0.032; 0.042)	0.034 (0.030; 0.039)	ns	Both: ns; 90>360[a]; ns
Turning duration (s)	0.206 (0.126; 0.288)	0.273 (0.209; 0.327)	0.278 (0.222; 0.368)	0.242 (0.196; 0.292)	0.239 (0.179; 0.293)	0.333 (0.304; 0.368)	ns	ns
Number of Steps (-)	0.367 (0.206; 0.531)	0.510 (0.372; 0.632)	0.470 (0.387; 0.595)	0.456 (0.398; 0.532)	0.426 (0.314; 0.508)	0.552 (0.498; 0.610)	ns	ns
Cadence (steps/min)[#]	2.87 (2.38; 3.38)	2.68 (2.24; 3.11)	3.16 (2.61; 3.69)	4.07 (3.25; 4.85)	4.05 (2.86; 5.37)	3.50 (2.54; 4.47)	ns	ns
Stride length: internal leg (m)	0.06736 (0.05168; 0.08218)	0.1655 (0.1500; 0.1800)	0.1302 (0.1154; 0.1461)	0.0706 (0.0552; 0.0863)	0.1082 (0.0959; 0.1197)	0.1045 (0.0862; 0.1253)	90°: ns 180°: E<Y[c] 360°: ns	Y: 90<180[c]; 90<360[b]; 180>360[b] E: 90<180[b]; 90<360[a]; ns
Stride length: external leg (m)	0.0551 (0.0438; 0.0697)	0.1047 (0.0859; 0.1248)	0.0998 (0.0813; 0.1178)	0.0726 (0.0533; 0.0921)	0.0849 (0.0664; 0.1092)	0.0675 (0.0586; 0.0775)	90°: ns 180°: ns 360°: E<Y[b]	Y: 90<180[a]; 90<360[a]; ns E: ns; ns; ns
Step length: internal leg (m)	0.0481 (0.0318; 0.0716)	0.0911 (0.0785; 0.1049)	0.0843 (0.0716; 0.0964)	0.0625 (0.0504; 0.0738)	0.0976 (0.0834; 0.1135)	0.0786 (0.0666; 0.0921)	ns	Both: 90<180[c]; 90<360[b]; 180>360[a]
Step length: external leg (m)[#]	0.0368 (0.0248; 0.0486)	0.0623 (0.0488; 0.0751)	0.0591 (0.0484; 0.0709)	0.0477 (0.0353; 0.0602)	0.0518 (0.0412; 0.0646)	0.0412 (0.0335; 0.0502)	90°: ns 180°: ns 360°: E<Y[a]	Y: 90<180[a]; ns; ns E: ns; ns; 180>360[a]
Stride width: internal leg (m)[#]	0.0586 (0.0421; 0.0775)	0.0747 (0.0620; 0.0883)	0.0473 (0.0377; 0.0562)	0.0425 (0.0368; 0.0500)	0.0377 (0.0312; 0.0454)	0.0344 (0.0301; 0.0385)	90°: ns 180°: E<Y[c] 360°: ns	Both: ns; ns; 180>360[a]
Stride width: external leg (m)	0.0683 (0.0552; 0.0829)	0.0881 (0.0690; 0.1046)	0.0704 (0.0572; 0.0831)	0.0338 (0.0259; 0.04120)	0.0497 (0.0402; 0.0596)	0.0444 (0.0380; 0.0508)	90°: E<Y[c] 180°: E<Y[b] 360°: E<Y[b]	Both: 90<180[a]; ns; 180>360[a]
Gait cycle duration: internal leg (s)[#]	0.0364 (0.0315; 0.0410)	0.0522 (0.0459; 0.05889	0.0540 (0.0463; 0.0620)	0.0445 (0.0334; 0.0543)	0.0685 (0.0529; 0.0865)	0.0608 (0.0506; 0.0714)	ns	Both: 90<180[c]; 90<360[c]; ns
Gait cycle duration: external leg (s)[#]	0.0284 (0.0224; 0.0342)	0.0363 (0.0295; 0.0435)	0.0400 (0.0346; 0.0462)	0.0423 (0.0285; 0.0564)	0.0558 (0.0429; 0.0693)	0.0518 (0.0408; 0.0629)	90°: ns 180°: E>Y[b] 360°: ns	Both: ns; 90<360[a]; ns
Stance duration: internal leg (s)	0.0338 (0.0275; 0.0399)	0.0395 (0.0342; 0.0451)	0.0402 (0.0363; 0.0445)	0.0333 (0.0266; 0.0404)	0.0495 (0.0402; 0.0595)	0.0462 (0.0387; 0.0534)	ns	Both: 90<180[b]; 90<360[b]; ns
Stance duration: external leg (s)[#]	0.0241 (0.0189; 0.0290)	0.0308 (0.0254; 0.0368)	0.0315 (0.0285; 0.0346)	0.0330 (0.0262; 0.0402)	0.0417 (0.0327; 0.0505)	0.0410 (0.0334; 0.0492)	ns	Both: 90<180[c]; 90<360[c]; ns
Initial double-support duration: internal leg (s)	0.0120 (0.0100; 0.0142)	0.0171 (0.0140; 0.0206)	0.0178 (0.0162; 0.0195)	0.0152 (0.0125; 0.0183)	0.0239 (0.0209; 0.0272)	0.0234 (0.0196; 0.0281)	90°: ns 180°: E>Y[a] 360°: E>Y[a]	Both: 90<180[c]; 90<360[c]; ns
Initial double-support duration: external leg (s)[#]	0.0136 (0.0117; 0.0158)	0.0153 (0.0128; 0.0175)	0.0166 (0.0144; 0.0192)	0.0133 (0.0104; 0.0162)	0.0194 (0.0153; 0.0238)	0.0174 (0.0148; 0.0203)	ns	Both: 90<180[a]; 90<360[a]; ns
Stance/cycle ratio: internal leg (%)	1.13 (0.927; 1.39)	1.45 (1.20; 1.71)	1.56 (1.36; 1.77)	1.46 (1.16; 1.86)	1.90 (1.60; 2.24)	1.95 (1.72; 2.23)	90°: ns 180°: ns 360°: E>Y[a]	Both: 90<180[b]; 90<360[b]; ns
Stance/cycle ratio: external leg (%)	1.44 (0.964; 1.92)	1.54 (1.29; 1.80)	1.48 (1.28; 1.72)	1.18 (0.937; 1.45)	1.87 (1.49; 2.44)	1.55 (1.35; 1.75)	ns	Both: 90<180[a]; ns; ns

Statistically significant ANOVA results ($p < 0.05$) are highlighted in green when there was an effect of age or turning amplitude, and in brown when there was an age x amplitude interaction.

Only statistically significant differences in post-hoc analyses are reported ([a]: $p < 0.05$, [b]: $p < 0.01$, [c]: $p < 0.001$).
#Non-parametric tests (ANOVA on a rank transformed scale)
Y: young adults, E: elderly adults.
90°: quarter-turn, 180°: half-turn, 360°: full-turn.

4. Discussion

The spatiotemporal parameters during turning maneuvers differed statistically between young and elderly adults. For most turning amplitudes, elderly were slower, needed more time and steps to turn and the spatial parameters of the internal and external legs were increased (Fig. 3). Furthermore, the initial double support duration and the stance/cycle ratio were increased in the elderly. However, there was no statistically significant difference in cadence, stance duration and gait cycle duration between young and elderly. These results extend our understanding of the differences in turning biomechanics with respect to ageing and confirmed the findings of prior works that studied a limited number of parameters, particularly regarding slower speed [6], longer step duration [5], shorter step length [6] and more steps [5] in older participants.

It is worth highlighting that, although stance duration was not different between young and elderly adults, the initial double-support duration and stance/cycle ratio were substantially higher in the elderly. These temporal differences may well be a mechanism to compensate for instability, by reducing the duration of less stable single-support.

On average both young and elderly adults used a cross-over turning strategy, which is shown by the negative stride width of the external leg. However, while the young adults adapted their stride width to the turning amplitude, increasing their base of support during turns of larger amplitudes, such an adaptation was not observed in the elderly [4]. This absence of stride width adaptation could be related to weaker muscles in the elderly [18]. Interestingly, stride width and stride width variability of the external leg are the measures that showed the most substantial differences between young and elderly adults, suggesting that stride width could be a key element of the ageing turning pattern. Since, during turning, stride width is related to the amount of lateral motion, the observation of differences in this parameter is consistent with prior reports of lateral instability in elderly adults [19,20]. More falls with hip fractures occur during turning than straight-line walking in the elderly [3]. This higher occurrence could be linked to an impaired capacity to adjust stride width, leading to increased instability and higher fall risks.

In short elderly adults seem to struggle adapting their spatiotemporal parameters to the increased gait difficulty while turning.

All these coherent observations, while preliminary, suggest that selective rehabilitation could improve walking biomechanics in the elderly, for example by enhancing strength and dexterity of frontal-plane muscles (e.g. adductor magnus, gluteus medius [21]) or practicing leg placements [22,23].

Interesting variations in spatiotemporal parameters were observed with respect to the turning amplitudes. Regarding group comparisons, several differences (e.g., turning duration, number of steps, and initial double support duration) were only observed at larger turning amplitudes (180° or 360°). Regarding changes among turning amplitudes, most of the parameters either showed no change (e.g., cadence, stride width of the internal leg and gait cycle), continuous changes from 90° to 180° and 360° (e.g., speed, turning duration and step length of the internal leg), or changes between 90° and the two other amplitudes (e.g., stance duration of the internal leg and initial double support duration). Altogether, this suggests a cut-off in turning biomechanics between 90° and 180°. This is an important finding for the design of future protocols as there could be an interest in testing at least two amplitudes: 90° turns as well as turns of 180° or more.

At a smaller turning amplitude (90°) the only difference in variability between young and elderly adults was with stride width of the external leg, which, as discussed above, seemed to be a particularly sensitive parameter. However, age-related differences in the variability of other parameters were observed at higher turning amplitudes (180° and 360°). This appears consistent with straight-line walking literature and the assumption that turning is a more challenging task than straight-line walking. Indeed, in prior straight-line gait studies, the variability was reported to remain fairly stable with respect to age [24], but to increase with pathologies [16] and falling history [25]. Therefore, in the future, analyzing turning and particularly parameters variability could allow detecting gait impairment sooner than the analysis of straight-line walking.

Since it is currently more common to analyze gait during straight-line than turning trials, there is an interest in comparing the present results with straight-line literature. During straight-line walking, previous studies mainly showed age-related differences in stride width [26], speed, step length, stance/cycle ratio and stride length [27–30], and no obvious differences were reported for the other spatiotemporal parameters analyzed in the present study, such as cadence [27,28,30]. These previous results seem consistent with the present data when turning at 90°. However, differences in other parameters were observed between age groups when turns of larger amplitudes were analyzed. Again this suggests that turning is more demanding than straight-line walking and could enhance the sensitivity to detect biomechanical differences, particularly at larger turning amplitudes. This well agrees with previous literature showing higher sensitivity to age-related differences with more challenging straight-line walking (i.e., during fast-walking) [20,31].

This study has some characteristics that should be discussed. First, the analyses were performed on the average and variability of the spatiotemporal parameters within each trial. This approach had the advantage of erasing the differences among trials (e.g., initiation with the left or right leg or differing number of steps) and mimicking the analysis usually done in straight-line walking studies. However, no characterization by turning phases was possible with this approach, and further research will be necessary to investigate the turning biomechanics at particular events/periods of the turning maneuvers. Second, turns at normal walking speed were analyzed, but additional insights could certainly be gained by recording trials at different speeds. Specifically, it could be interesting studying an even more challenging task consisting in turning at a faster-than-normal speed. Third, while the sample size could appear limited, it is worth reminding that the statistical analysis was based on 540 trials and that the statistical power was increased by the use of a mixed design, combining between-subject and within-subject factors. The sample size was furthermore adequate in view of exploratory objectives of the study. Finally, studies with patients will be necessary to further advance our understanding of turning biomechanics.

5. Conclusions

This study extends our understanding of turning biomechanics with respect to ageing. Specifically, stride width was found to be a key difference of the ageing turning pattern. This study also suggested paying particular attention to the turning amplitude when analyzing data or designing a study, since turning at 90° was shown to differ from turning at larger amplitudes (180°, 360°). Analyzing turns of larger amplitudes may enhance the sensitivity to detect age-related differences. Finally, our results may pave the way for new selective rehabilitation protocols, which could improve walking biomechanics in the elderly.

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Conflicts of interest

Authors declare no conflicts of interest.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2022.11.010.

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