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ORIGINAL RESEARCH

Walking Parameters of Older Adults on Hilly and Level Terrain Outdoors

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Background/Objective: To understand how older adults adapt their walking to various environments, it is important to study walking outdoors, including on hilly terrain. This cross-sectional study aimed to validate inertial measurement units (IMUs) for detecting older adults' walking parameters on uphill and downhill terrains and to compare these parameters between level and hilly terrains. ***Methods:*** A sample of older adults ($N = 35$; $M_{\text{age}} = 76$ years, $SD = 5$; 71% women) walked on a level, uphill, and downhill route outdoors at self-selected speeds. Three IMUs were used to estimate walking parameters (step, stride, swing, and stance durations; cadence; step length; and walking speed). IMUs were validated against high-speed video camera data from six participants. After validation, differences in walking parameters between the three terrains were assessed with repeated measures analysis of variance and variability of the parameters (SD/mean × 100%) with Friedman's test. ***Results:*** IMUs showed mainly good to excellent validity for temporal but not spatial walking parameters in hilly outdoor environments. Older adults exhibited longer step, stride, and swing durations, and lower cadence on level and uphill versus downhill. On level terrain, cadence was higher, and step, stride, and stance durations were shorter than uphill. Variability of temporal parameters was greatest uphill. ***Conclusion:*** IMUs demonstrated potential to measure walking parameters of older adults in hilly terrain. The results suggest that older adults' outdoor walking parameters differ between level and hilly terrain. ***Significance/Implications:*** These results can inform the design of outdoor walking interventions for older adults by considering the usability of IMUs and the changes in walking parameters due to environment.

Keywords: gait analysis, validation, IMU, uphill, downhill

Key Points

- Inertial measurement units seem to be valid to detect temporal walking parameters of healthy older adults walking uphill and downhill outdoors.
- Temporal walking parameters varied more during uphill walking compared with level and downhill walking outdoors.
- Older adults walked with longer step, stride, and swing durations and lower cadence on level and uphill compared with downhill.

Walking is a complex movement that requires cooperation between the central and peripheral nervous systems, including feedback from muscles, joints, and other receptors (Vaughan et al., 1992, p. 2). Aging has widespread effects on the human musculoskeletal, nervous, respiratory, and circulatory systems (Komulainen & Vuori, 2015[2016]) and causes motor (McGibbon, 2003) and sensory deficits (Seidler et al., 2010). Aging also influences spatiotemporal walking parameters such as step/stride and swing/stance durations, step length, cadence, and step velocity (Dewolf et al., 2021; Hong et al., 2015; Kuntapun et al., 2020; Thomson et al., 2019). For example, it seems that older adults walk slower (Hollander et al., 2022; Hong et al., 2015; Schmitt et al., 2021), take shorter strides than younger adults at a given speed (Dewolf et al., 2021; Hollander et al., 2022; Kuntapun et al., 2020), and show increased variability in stride (Bock & Beurskens, 2010; Hausdorff et al., 2001) and step durations and cadence (Gamwell et al., 2022). Variability of swing duration also seems to increase with age (Shafizadeh et al., 2023).

Environment is another factor that influences walking, as reflected by changes in walking parameters (Ferraro et al., 2013; Hong et al., 2015; Lindemann et al., 2017; Thomson et al., 2019; Scaglioni-Solano & Aragón-Vargas, 2015). Walking on hilly terrain is more physically demanding than on level terrain (Scaglioni-Solano &

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Aragón-Vargas, 2015) and imposes unique mechanical demands on the neuromuscular system (Lay et al., 2006). During downhill walking, there is a greater risk of falling because the increased acceleration may disturb gaze and posture (Scaglioni-Solano & Aragón-Vargas, 2015). When older adults walk indoors on an uphill slope with different gradients, they walk with a lower cadence and a longer double stance duration as the steepness of the slope increases (Hong et al., 2015), whereas during pronounced outdoor downhill walking, they walk slower, with shorter steps and higher cadence than on level terrain or on a moderate downhill (Scaglioni-Solano & Aragón-Vargas, 2015). During indoor and outdoor uphill walking, older adults walk slower with shorter strides and lower cadence compared with level walking (Ferraro et al., 2013; Lindemann et al., 2017; Thomson et al., 2019). However, only a few studies have compared spatiotemporal parameters of older adults walking outdoors on level terrain with both uphill and downhill (Scaglioni-Solano & Aragón-Vargas, 2015; Thomson et al., 2019). Thus, it remains unclear how walking parameters are modified when older adults walk on different terrain outdoors.

Walking outdoors in a free-living environment differs from walking in a laboratory (Brodie et al., 2016; Hillel et al., 2019; Schmitt et al., 2021) due to variation in environmental conditions, such as light, sound, and ground surface. Despite that, walking has mainly been assessed indoors and on level terrain in the past. Instrumented gait analysis can reveal subtle changes in gait that cannot be detected in clinical assessment or based only on walking speed (Zhang et al., 2021), and laboratory measurements, such as three-dimensional motion capture and electronic walkways have been used to assess walking parameters. Inertial measurement units (IMUs; with three-dimensional accelerometer, gyroscope, and magnetometer) and custom algorithms have recently been used to estimate spatiotemporal walking parameters, enabling walking to be assessed outdoors in more natural environments (Schmitt et al., 2021; Thomson et al., 2019). IMUs have been shown to be valid measurement tools to assess spatiotemporal walking parameters in older adults indoors (O'Brien et al., 2019; Rantalainen et al., 2019; Werner et al., 2020), and good validity of temporal walking parameters has been reported outdoors (Matikainen-Tervola et al., 2024). However, very few studies have used IMUs to examine spatiotemporal walking parameters of older adults on different terrains outdoors. Moreover, to our knowledge, the validity of IMUs to assess spatiotemporal walking parameters outdoors on hilly terrain has not yet been studied in older individuals.

The aims of this cross-sectional study were: (a) to demonstrate the validity of IMUs for estimating spatiotemporal walking parameters in outdoor hilly terrain and (b) to assess how walking parameters change when older adults walk outdoors on level, uphill, and downhill terrain. Based on our previous studies on validity of IMUs on level environment (Matikainen-Tervola et al., 2024), we hypothesize that IMUs are valid to detect walking parameters also on uphill and downhill walking. We also anticipate finding differences in walking parameters between level, uphill, and downhill walking.

Methods

Study Type and Participants

This study is part of a larger experimental cross-sectional research project Gait features in different environments contributing to participation in outdoor activities in old Age (GaitAge). Full details of the project and methodology have been reported previously (Rantakokko et al., 2024).

Briefly, 40 community-dwelling older adults aged 70 and older, without severe sensory deficits, memory impairment, or neurological condition, and able to walk at least 1 km without assistive devices took part in the study. From six of these participants, valid IMU data were obtained from five uphill and five downhill trials and used in a validation substudy. To compare walking parameters in different terrains, 35 out of 40 participants from whom data were obtained on level, uphill, and downhill outdoor terrains were included in this study. The study followed the principles of the Declaration of Helsinki and was approved by the ethics committee of JAMK University of Applied Sciences (JAMK 40/13.02.2021). All participants gave their written informed consent prior to any measurements, and they could withdraw at any time during the study.

Procedure

Data collection included two visits: Anthropometry (height and body mass) was assessed in the first visit, and outdoor walking measurements were performed in the second visit, which was approximately 7 days later (range: 2–20). Outdoor measurements were conducted only on summer and autumn days without rain.

In the level outdoor walking test, participants walked on a public sport track along a 70-m route (2 × 29 m straight path and turns) for 6 min. In uphill and downhill walking tests, participants walked five times along a 20-m-long straight asphalt route on a 5° hill (8.7%), alternating between downhill and uphill. All tests were conducted at self-selected, normal walking speeds.

Participants wore three IMU sensors (NGIMU, x-io), which contained a three-dimensional accelerometer (range: 16 g), gyroscope (range: 2,000°/s), and magnetometer (range: 13,000 μT). Sensors were attached with Velcro tape to the lower back, middle of the spine at the level of L3–L4 and laterally midway along each shank. The lower back IMU was attached to a small wooden plate to avoid unnecessary tilting and rotation of the sensor caused by the shape of the lower back during walking.

Walking was filmed with a high-speed camera (GoPro9 HERO, GoPro Inc.) from the side of the participant at a distance of 3.46 m during the level test and 4.25 m during uphill and downhill tests. Sampling frequency was 120 frames per second. The camera was attached to a three-wheeled trolley, which was moved by a researcher alongside the participant as they walked.

Data Analysis

Validity of IMU Sensors

Validation of IMU sensors in uphill and downhill walking was performed on six participants from whom valid, synchronized IMU data were obtained from all five uphill and five downhill trials. As a reference, a high-speed GoPro camera was used. The validity of IMU sensors for detecting spatiotemporal walking parameters on level terrain outdoors has been validated previously (Matikainen-Tervola et al., 2024).

From IMU sensors, step events (heel strike and toe off) were detected with an algorithm developed previously (Aminian et al., 2002; Bertoli et al., 2018; Madgwick et al., 2011; Renggli et al., 2020; Vähä-Ypyä et al., 2018; Zijlstra & Hof, 1997, 2003). Zero-crossings of the anteroposterior acceleration of the lower back IMU were used to denote heel strike (Zijlstra & Hof, 2003). The global minimum of the sagittal angular velocity of the shank IMUs was used to represent toe off (Aminian et al., 2002; Bertoli et al., 2018; Renggli et al., 2020). Step length estimation was done by assuming compass gait with an inverted pendulum and using the vertical acceleration signal of the lower back IMU and heel strike events. The formula for step length calculation was:

$$\text{Step length} = 2\sqrt{(2lh - h^2)},$$

where l is the length of the pendulum (leg length) and h is the vertical displacement (Zijlstra & Hof, 2003). Leg length was estimated as $0.53 \times$ participant's height (Winter, 1979).

From IMU data, step and stride durations, swing and stance durations, cadence, step length, and walking speed were calculated as shown in Table 1. The first and last heel strikes for each trial were excluded. Other algorithm and filtering details are reported in the Supplementary Material S1 (available online).

From the reference, high-speed video camera data, heel strikes, and toe offs were identified manually. Heel strike was defined as the first contact of the shoe with the ground and toe off as the moment just before the forefoot of the shoe left the ground. IMUs and video data were synchronized using an analog trigger device that produced a transistor-transistor logic pulse in the IMU analog channel and a red light visible in the camera view at the beginning of a recording. From the reference, cadence and step, stride, swing, and stance durations were calculated as from IMU data (Table 1). From the reference data, step length was calculated by dividing the length of the route (20-m) by the number of individual steps taken during the route, and walking speed was calculated as the distance walked divided by time.

Walking Parameters in Different Terrains Outdoors

In the analysis of IMU data, steps from the first and second available walking trials for each terrain were used to minimize the impact of tiredness on walking parameters. In the level test, a trial consisted of a 29-m-long straight walking path between the turns. In the uphill and downhill tests, a trial consisted of a 20-m-long straight walking path on a 5° hill (8.7%). The two first and last heel strikes were excluded from each trial in the analysis. The same algorithms were used to calculate walking parameters from IMU data from level, uphill, and downhill terrains as in the validation tests in this study and previously in Matikainen-Tervola et al. (2024). If the algorithm identified the wrong peak for heel strike or toe off (based on visual inspection), the stride in question was not used in the analysis ($N = 5$). One participant had toe-off events from uphill and downhill walking IMU data only from another leg.

Statistical Analysis

Validation of IMUs in Uphill and Downhill Outdoors

Bland–Altman plots (Bland & Altman, 1986), typical errors (*SD* divided by $\sqrt{2}$), and root mean square errors were drawn and calculated for each spatiotemporal walking parameter and for step events (heel strike and toe off). Intraclass correlation coefficients (ICCs) with absolute agreement (2,1) were calculated for each spatiotemporal walking parameter. ICC values were defined as excellent (≥.75), good (.60–.74), fair (.4–.59), or poor (<.4; Cicchetti, 1994).

Walking Parameters in Different Terrains Outdoors

Mean, *SD*, and variability (coefficient of variation $\% = SD/\text{mean} \times 100$) were calculated for walking parameters from all three terrains. Normality of variables was estimated with the Shapiro–Wilk test and Q–Q plots. Repeated measures ANOVA was used to test the differences between walking parameters on different terrains and Friedman's test to test the differences between variability of walking parameters on those terrains. For parametric tests, sphericity was estimated with Mauchly's *W* test. If the assumption of sphericity was violated, Greenhouse–Geisser correction was used. Bonferroni correction was used for post hoc analysis. Post hoc comparisons for nonparametric tests were done with Wilcoxon signed ranks test. Statistical tests were done with JASP (version 0.18.3.0, JASP Team 2024) and SPSS (version 29.0).

Results

Validation of IMUs in Uphill and Downhill Outdoor Walking

In the validation substudy, the mean age of the participants ($N = 6$) was 74 years ($SD = 3$; range: 69–77) and five out of six were female. Mean height was 164 cm (range: 154–170 cm; $SD = 6$) and mean body mass 65 kg ($SD = 14$). In the analysis, 824 heel strike and 823 toe off events from uphill walking, as well as 811 heel strike and 809 toe off events from downhill walking were included.

When IMU values were compared with high-speed camera values, bias for heel strike varied from −0.001 s uphill to −0.016 s downhill, with root mean square errors and typical errors of 0.02 s for both terrains. For toe off, bias was −0.061 s uphill and −0.052 s downhill, and typical errors were 0.02 and 0.03 s, respectively. For cadence, bias was −0.15 steps/min for uphill and −0.06 steps/min for downhill, and corresponding typical errors were 3.60 steps/min and 2.69 steps/min. In uphill, bias was −0.06 s for stance duration and 0.06 s for swing duration, with corresponding values of −0.04 and 0.04 s for downhill. ICCs (2,1) were excellent for step and stride durations uphill and downhill and stance duration during downhill walking, fair for uphill stance duration, and poor for other parameters. Bias for step length estimation was 2.4 cm and for walking speed 0.04 m/s during uphill walking. In downhill walking, bias for step length estimation was 11.25 cm and for walking speed 0.238 m/s. Bland–Altman plots, ICCs, bias and its *SD*, root

Table 1 Definitions of Spatiotemporal Walking Parameters Based on Inertial Measurement Units Used in This Study

Parameters	Definition
Step duration	Time between two consecutive contralateral heel strikes in seconds
Stride duration	Time between two consecutive ipsilateral heel strikes in seconds
Swing duration	Time between consecutive toe off and heel strike of the same foot in seconds
Stance duration	Time between consecutive heel strike and toe off of the same foot in seconds
Cadence	60/step duration, steps per minute
Step length	Length calculated between two consecutive contralateral heel strikes with the methods of Zijlstra and Hof (1997, 2003) using an inverted pendulum model adjusted for leg length in centimeters
Walking speed	The sum of the step lengths divided by the time taken in meters per second

mean square error, and typical errors for all walking parameters are reported in the Supplementary Material S2 (available online).

Because the validity of IMU estimates of step length and walking speed downhill was limited, only temporal walking parameters (step, stride, swing, stance durations and cadence) were further compared between level, uphill, and downhill conditions.

Walking Parameters in Different Outdoor Terrains

Participants ($N = 35$) whose outdoor walking parameters from IMU data were compared in different terrains were 69–92 years old ($M_{\text{age}} = 76$ years, $SD = 5$) and 71% of them were female ($N = 25$). Mean height was 165 cm (range: 150–184 cm, $SD = 9$) and mean body mass 72 kg ($SD = 13$). Mean walking speed, assessed from video data from the first trial on all terrains, was 1.42 m/s ($SD = 0.17$) on level, 1.34 m/s ($SD = 0.19$) in uphill, and 1.39 m/s ($SD = 0.21$) in downhill walking.

Statistically significant differences in mean values were found for step duration ($p < .001$), stride duration ($p < .001$), swing duration ($p < .001$), stance duration ($p < .001$), and cadence ($p < .001$) on different terrains. Raincloud plots of walking parameters are shown in Figure 1, and mean values for walking parameters in different environments are presented in detail as Supplementary Material S3 (available online).

Post hoc comparisons revealed that cadence was lower and step, stride, and swing durations were longer on level and uphill terrain compared with downhill (Table 2). Cadence was higher and

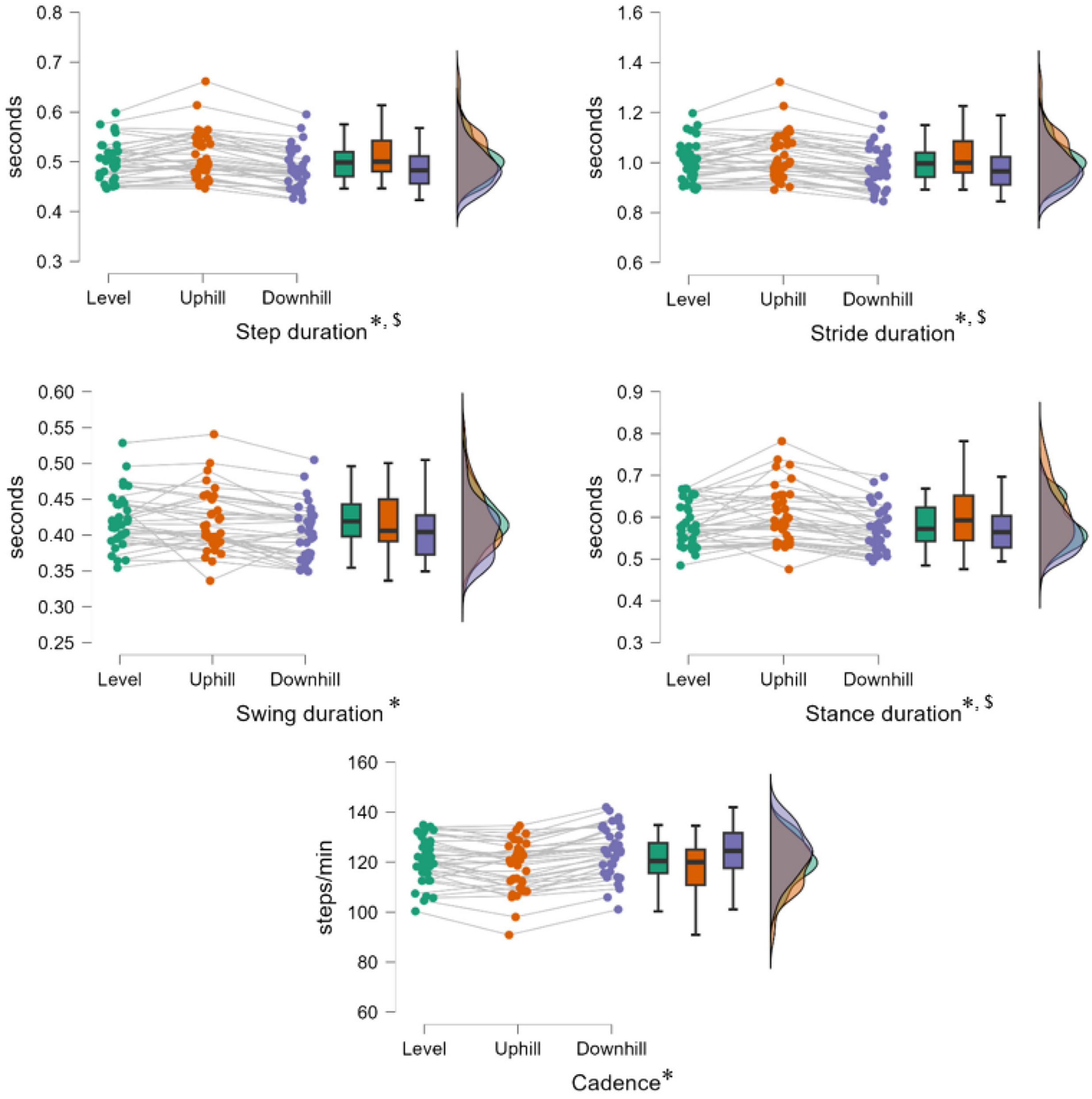

Figure 1 — Raincloud plots of mean walking parameters (step and stride duration, cadence and swing, and stance duration) of older adults' walking outdoors in level, uphill, and downhill terrain. *Note*. Differences between terrains measured with repeated-measures analysis of variance. $^*p < .001$. $^\$$Sphericity violated, Greenhouse–Geisser correction used. Post hoc comparisons are presented in Table 2.

Table 2 Post Hoc Comparison With Bonferroni Correction of Mean of the Walking Parameters of Older Adults Between Outdoor Terrains

Parameter	Terrains comparison	Mean difference	*SE*	*t*	$p_{\text{Bonferroni}}$
Step duration (s)	Level vs. uphill	–0.012	0.003	–3.676	.001
	Level vs. downhill	0.014	0.003	4.368	<.001
	Uphill vs. downhill	0.026	0.003	8.044	<.001
Stride duration (s)	Level vs. uphill	–0.023	0.007	–3.574	.002
	Level vs. downhill	0.029	0.007	4.404	<.001
	Uphill vs. downhill	0.052	0.007	7.978	<.001
Swing duration (s)	Level vs. uphill	0.002	0.004	.588	1.000
	Level vs. downhill	0.017	0.004	4.109	<.001
	Uphill vs. downhill	0.015	0.004	3.521	.002
Stance duration (s)	Level vs. uphill	–0.025	0.007	–3.797	<.001
	Level vs. downhill	0.012	0.007	1.789	.234
	Uphill vs. downhill	0.036	0.007	5.586	<.001
Cadence (steps/min)	Level vs. uphill	2.498	0.721	3.466	.003
	Level vs. downhill	–3.619	0.721	–5.021	<.001
	Uphill vs. downhill	–6.118	0.721	–8.487	<.001

Note. $N = 35$.

step, stride, and stance durations were shorter on level terrain compared with uphill. Swing duration did not differ between level and uphill terrains.

Statistically significant differences were found between variability of step ($p = .005$), stride ($p < .001$), and swing durations ($p = .013$), and cadence ($p = .005$) in different terrains. Variability of stance duration ($p = .196$) did not differ statistically between terrains (Figure 2). Mean values for variability of walking parameters in different environments are presented in detail as Supplementary Material S3 (available online).

Post hoc comparisons for variability values revealed that in the uphill condition, cadence and stride duration varied more compared with downhill (Table 3). Step, stride, and swing durations and cadence varied more in uphill than on the level. Step and stride durations and cadence also varied more in uphill than in downhill. Cadence varied more in downhill than on the level.

Discussion

The first aim of this study was to examine the validity of IMUs for assessing walking parameters of older adults outdoors in uphill and downhill terrain. IMUs exhibited good to excellent validity for uphill and downhill temporal walking parameters and reasonable validity for swing duration both uphill and downhill. For spatial walking parameters, validity was good in uphill but not downhill walking. The second aim was to quantify changes in walking parameters of older adults between level, uphill, and downhill terrain. Uphill walking resulted in the lowest cadence and the longest step, stride, and stance durations. In downhill walking, step, stride, and swing durations were shortest, and cadence was highest. Step, stride, and swing durations and cadence varied the most in uphill walking. These changes in outdoor walking parameters seem to reflect the demand faced by older adults particularly when walking uphill.

Our IMU validation results for estimating spatiotemporal walking parameters in hilly terrain are consistent with those of previous studies done on level terrain with IMUs or accelerometers, whereby temporal parameter validity was good to excellent apart from swing duration (Del Din et al., 2016; O'Brien et al., 2019; Pepa et al., 2017). In our study, swing duration estimation bias with IMUs was 0.05–0.06 s. This was due to toe off estimation bias of –0.6 s for uphill walking and –0.04 s for downhill walking. In the uphill condition, spatial parameters showed good validity but not in downhill walking. Step length estimation with IMUs is inherently variable and challenging for several reasons. In older adults, during downhill walking, the pelvic region undergoes increased acceleration compared with level walking (Scaglioni-Solano & Aragón-Vargas, 2015). The model for step length estimation with IMUs is rigid (O'Brien et al., 2019); it assumes the leg to be one stiff segment and does not consider movement of the hip, knee, or ankle. Because we used the same model for all terrains, it did not perfectly reflect the mechanical demand of downhill walking. For these reasons, step length and walking speed were not compared between level and hilly terrains.

Walking uphill is more physically demanding than walking on a level surface or downhill. The center of mass of the body must be raised during uphill walking (Dewolf et al., 2021), and muscle activity is increased compared with level walking (Dewolf et al., 2019; Franz & Kram, 2012). Older adults' lower limb muscle activity has been shown to be higher during uphill walking compared with downhill or level walking (Tikkanen et al., 2016). Thus, during uphill walking, the propulsive requirements of the leg are higher than in level walking (Lay et al., 2006). Older adults typically have impaired leg propulsion during uphill walking because they generate significantly less ankle power during the push-off phase than younger adults (Franz & Kram, 2014). Kinematics and joint moments in uphill walking have also been shown to differ from level walking, potentially indicating unique control strategies between terrains (Lay et al., 2006). These factors may explain why walking varied the most in uphill, and cadence and other temporal parameters differed between uphill and downhill.

In downhill walking, modifications are needed to accommodate the increased acceleration demands. Kinematics, ground reaction forces, and joint moments have all been shown to differ between downhill and level walking (Lay et al., 2006). In downhill walking, knee extensor muscle activity increases (Franz & Kram,

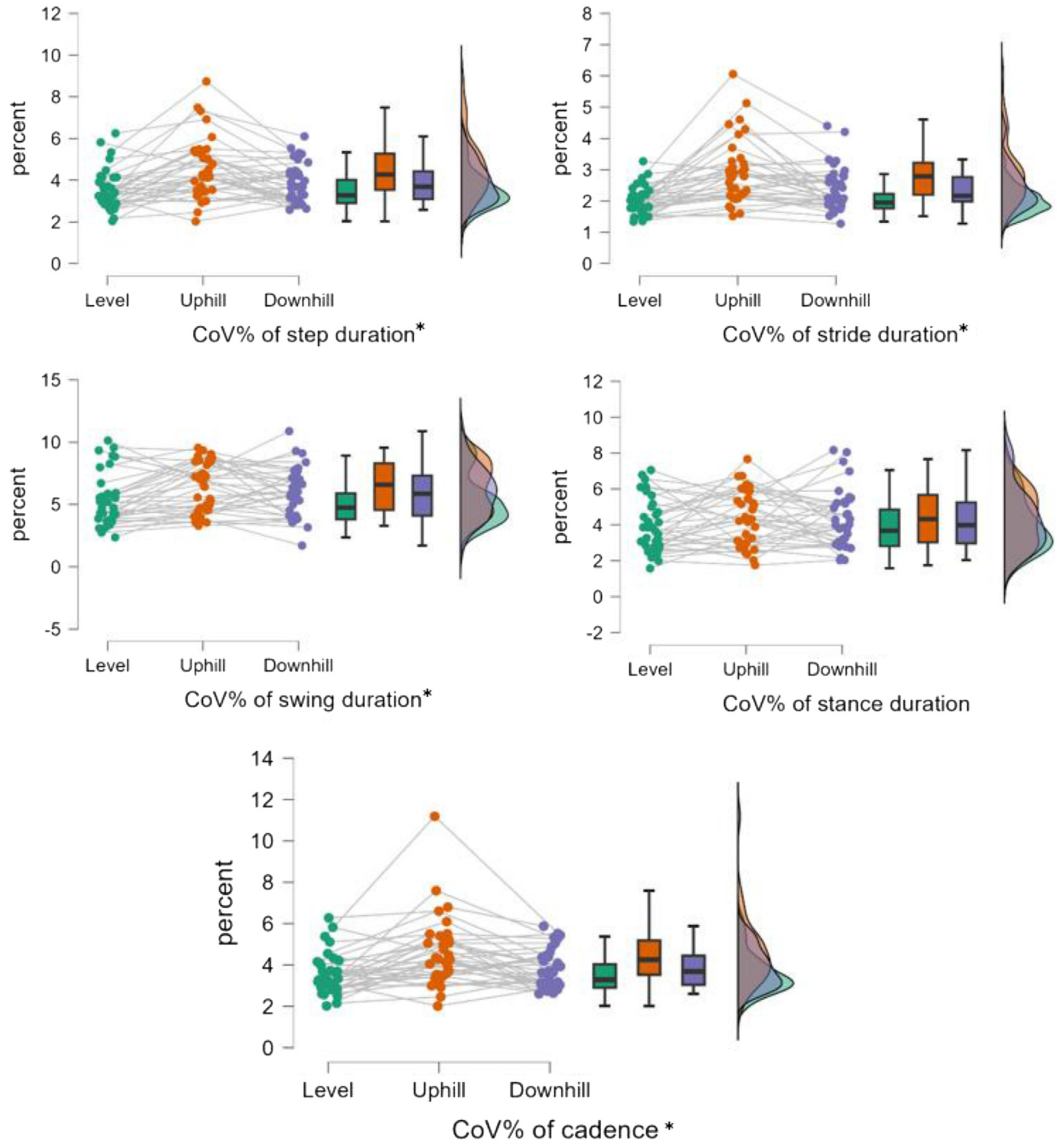

Figure 2 — Raincloud plots of the variability (CoV%) of walking parameters (step, stride, swing, and stance durations and cadence) of older adults' walking outdoors in level, uphill, and downhill terrain. *Note*. Differences between variability in terrains measured with Friedman's test. Post hoc comparisons are given in Table 3. CoV% = coefficient of variation %. $^{*}p < .05$.

2012) and oxygen consumption decreases compared with level walking (Gault et al., 2013). Walking downhill requires different neural activation than uphill walking (Dewolf et al., 2021). In this study, older adults walked outdoors with higher cadence in downhill versus level terrain and level versus uphill. These results are consistent with those of previous studies of older adults walking in level and hilly environments (Ferraro et al., 2013; Thomson et al., 2019; Twardzik et al., 2019). Scaglioni-Solano and Aragón-Vargas (2015) reported differences in cadence between level, and steeper downhill walking, but did not examine uphill walking. In our study, there was no statistical difference in variability of step duration between level and downhill walking, which is in line with the results of Scaglioni-Solano and Aragón-Vargas (2015).

In addition to the effects of terrain on walking mechanics, outdoor environments also introduce other challenges such as variable weather conditions and the presence of other people. Level walking was done on a sport track and hilly walking in pedestrian area outdoors, both away from any major traffic, and in clear weather. Older adults have been shown to increase the variability of walking in response to perturbed visual feedback (Francis et al., 2015). During hilly tests, other people were passing by near the walking test area, and although they did not cross the

Table 3 Post Hoc Comparison of Variability of Walking Parameters of Older Adults Between Outdoor Terrains

Parameter	Terrains comparison	*Z*	$p_{\text{Bonferroni}}$
Step duration (CoV%)	Level vs. uphill	−3.800	<.001*
	Level vs. downhill	−2.097	.036
	Uphill vs. downhill	−2.752	.006*
Stride duration (CoV%)	Level vs. uphill	−4.815	<.001*
	Level vs. downhill	−3.243	.001*
	Uphill vs. downhill	−3.178	.001*
Swing duration (CoV%)	Level vs. uphill	−2.932	.003*
	Level vs. downhill	−1.998	.046
	Uphill vs. downhill	−1.048	.295
Cadence (CoV%)	Level vs. uphill	−3.767	<.001*
	Level vs. downhill	−1.965	.049
	Uphill vs. downhill	−2.670	.008*

Note. $N = 35$. CoV% = coefficient of variation %.
*Statistically significant difference according to Bonferroni correction ($p < .017$ [0.05/3]; Wilcoxon signed-rank tests).

walking route of the participant, their presence may have affected the variability of older adults' walking. Thus, there is scope for future research to examine the possible effects of these variables on walking patterns.

The main limitation of this study is that when validating step length and velocity in the downhill condition, poor ICC values were achieved with IMUs compared with high-speed video camera data. For this reason, we compared only temporal walking parameters across different terrains. In future, it would be important to develop a walking model and analysis approach that take into account the nature and requirements of downhill walking. In addition, we only studied relatively healthy older adults, so our results may not apply to different clinical populations.

In conclusion, IMUs are valid for estimating temporal parameters in hilly terrain especially but also spatial parameters in uphill terrain. Our research shows that there are changes in walking depending on the environment. Therefore, it is important to assess walking in outdoor "real-life" environments, which may tell us more about older adults possibilities of outdoor mobility than traditional walking measurements conducted in laboratory environments. These results could be utilized when planning walking programs or rehabilitation interventions for older adults, for example, by gradually introducing outdoor hilly walking sections and using IMUs to estimate walking parameters. In this way, the demand level could be progressively increased while allowing people to walk in more realistic outdoor environments compared with the typical laboratory environment.

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