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Influence of surface type on outdoor gait parameters measured using an In-Shoe Motion Sensor System

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ABSTRACT

The objectives of this study were to measure outdoor gait parameters using an In-Shoe Motion Sensor System (IMS) and evaluate how different types of surfaces affect various gait dynamics. Accurate outdoor gait data are crucial for effective fall risk assessment because surface irregularities and tripping hazards often result in falls during walking. An IMS was used in this study to collect spatiotemporal, spatial, and foot parameters from 27 healthy adults walking on indoor asphalt, soil, and grass surfaces. Data were recorded during a 6-minute walk test, with measurements taken every 2 min and analyzed using the Statistical Package for the Social Sciences. The results showed significant differences in foot clearance, heel height, and gait cycle across surfaces. Walking on grass significantly increased foot height, swing time, and roll angle of heel contact. These findings may help develop interventions to prevent falls.

1. Introduction

Walking plays a crucial role in daily life, enabling mobility and independence [1]. Daily walking occurs in various surface environments, from smooth indoor corridors to uneven outdoor terrain. Traditional gait analysis has been conducted using 3D motion capture systems in controlled settings, such as laboratory corridors or treadmills [2,3].

However, the advent of Inertial Measurement Units (IMUs) has revolutionized gait analysis by allowing the measurement of walking parameters in more natural outdoor environments, closely resembling daily life conditions [4–6]. IMUs enable easy and continuous movement tracking, which provides a comprehensive understanding of gait dynamics across different surfaces. For instance, a study comparing indoor corridors with outdoor interlocking block pavements reported an increased ankle angle during outdoor walking [7]. However, these studies primarily focused on the differences between indoor and outdoor conditions and did not consider comparisons among multiple surfaces. Another study using IMUs measured the gait on sidewalks, dirt paths, gravel, grass, and wood chips, highlighting the increased effort required on uneven terrain owing to higher energy cost [8]. Despite these advancements, studies that comprehensively compare temporal, spatial, and spatiotemporal gait parameters across various outdoor surfaces using IMUs are lacking.

Evaluating diverse gait parameters is essential for assessing overall daily activity levels, the extent of functional recovery post-injury, fall risk, and general endurance [9–12]. Specifically, a detailed gait analysis can reinforce rehabilitation strategies and fall prevention measures. Real-world conditions, where different surface types significantly affect walking stability and efficiency, necessitate such evaluations. Foot height and minimum toe clearance are crucial parameters often associated with tripping risk and walking stability [13,14]. Previous studies have shown that these parameters indicate the effect of overall gait efficiency and safety on individual adaptation to uneven surfaces. The roll angle is a critical indicator of the tarsal joint lock that can evaluate the rigidity and flexibility of the ankle, thereby influencing the kinetic chain of the lower limb [15]. Temporal parameters, such as cadence, stance time, and swing time, provide insights into the rhythm and balance of walking, which are essential for identifying potential gait impairments and designing appropriate interventions [16,17].

Therefore, this study aimed to evaluate and examine the effect of various walking surfaces on a wide range of gait parameters using IMUs. We sought to provide a detailed understanding of the influence of surface conditions on walking patterns by comparing gait dynamics on different surfaces—laboratory corridors, asphalt, dirt, and grass.

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We hypothesized that compared with indoor walking, outdoor walking exhibits larger spatial parameters, such as joint angles, and slower temporal parameters, such as walking speed and stance time. We expect the effects to be more pronounced in the order asphalt < dirt < grass, with grass among outdoor surfaces showing the most significant deviations owing to its uneven nature.

2. Materials and methods

2.1. Study design

This study utilized a cross-sectional design to investigate the research objectives.

2.2. Setting

The analysis of data was conducted at the facilities of Kyoto University (Kyoto, Japan).

2.3. Ethics statement

The study received approval from the Ethics Committee of the Graduate School and Faculty of Medicine, Kyoto University (approval no R3664–3). All participants gave written informed consent before participating in the study.

2.4. Participants

Participants were recruited from Kyoto University students. Eligibility criteria included individuals aged 18 years or older who could walk independently for at least 6 min without a break. Participants with neurological, orthopedic, cardiac, or respiratory conditions affecting mobility or walking were excluded.

2.5. Equipment

An In-shoe Motion Sensor System (IMS; A-RROWG, NEC Corporation, Tokyo, Japan) was employed for gait measurement. The IMS includes critical components such as an ARM Cortex-M4F microcontroller unit (nRF52832) by Nordic Semiconductor, featuring a 64 MHz CPU, 64 KB RAM, and 512 KB ROM. For precise movement tracking, it incorporates a Bosch IMU (BMI160), which measures 3-axis acceleration and angular velocity. The IMU has an accelerometer full-scale range of ±16 g with a sensitivity of approximately 0.488 mg/LSB, a gyroscope full-scale range of $\pm2000^\circ/s$ with a sensitivity of approximately $0.061^\circ/s/LSB$, and a sampling rate of 100 Hz. Additional components include an ABLIC EEPROM (S-24C32C, 32 K-bit) for data storage and an EPSON real-time clock (RX8130CE) for timekeeping.

The system captures gait parameters every 2 min, assessing both left and right sides. The device remains in sleep mode to conserve power and activates upon detecting motion. Specifically, the device uses a built-in high-g detection function to sense motion likely to be walking when the vertical acceleration exceeds 2 .25g. Upon detecting such motion, the device's microcontroller unit (MCU) wakes up, and the IMU's sampling rate is increased to 100 Hz. It measures three steps, either consecutive or non-consecutive, within 9 s of detecting walking initiation. If fewer than three steps are recorded, the system considers it a measurement failure. If more than three steps are recorded, only the first three steps are averaged. This process is repeated up to three times within one minute. If all attempts fail, the measurement is marked as a failure, and no data is stored. Stable-gait identification is performed by counting instances where posterior acceleration exceeds 3.5g , typically during foot contact in normal walking. If three such instances are detected within 5 s, the device confirms stable walking and proceeds to measure gait parameters. If this threshold is not met, the device returns to sleep mode to conserve power.

The system automatically calculates 16 parameters validated in previous studies [18–20], including walking speed, stride length, maximum dorsiflexion angle, maximum plantar flexion angle, foot height, circumduction, toe-in/toe-out angle, heel contact roll angle, toe-off roll angle, cadence, stance time, swing time, pushing time, peak swing angular velocity, maximum speed during the swing phase, and foot clearance. Table 1 defines these parameters as outlined by the IMU developer.

2.6. Procedures

Before the measurements began, participants were asked to wear their regular clothing and footwear, and their age, height, weight, and foot size were documented. Insoles containing the IMS were then placed inside their shoes, followed by a 5-meter walk test to confirm that they experienced no pain or discomfort while walking. The study assessed walking parameters on four surface types commonly encountered in daily life: a laboratory corridor, asphalt, dirt, and grass (Fig. 1). These surfaces were selected to represent a variety of walking conditions, ranging from the controlled environment of an indoor corridor to outdoor surfaces like smooth asphalt and more uneven terrain such as dirt and grass, which were used as baseline experimental conditions. The order of surface testing was randomized using Microsoft Excel's random function. Measurements on asphalt, dirt, and grass were only conducted on dry days with no standing water. Participants were instructed to walk back and forth along a 30-meter path at a comfortable, everyday pace for 6 min, carrying a smartphone in their pocket to collect data. Observers were positioned at each end of the route to monitor normal walking and ensure participant safety, providing time updates every minute. All measurements were completed on the same day, with rest breaks allowed upon participant request.

2.7. Statistical analysis

The average and standard deviation of the walking parameters over six minutes were calculated for each surface type. Statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS) version 22.0 (IBM Corp., Armonk, NY, USA). The normality of the data distribution was assessed using the Shapiro–Wilk test. Parametric

Table 1
Definition of measured parameters.

Parameters	Definition
Walking speed	Stride length divided by stride time
Stride length	Distance between two consecutive ground contacts of the same foot
Maximum (peak) dorsiflexion angle	Peak foot-sole angle in dorsiflexion
Maximum (peak) plantar flexion angle	Peak foot-sole angle in plantarflexion
Foot height	Maximum vertical height of the midfoot (sensor placement) during the foot trajectory
Circumduction	Displacement in the medial–lateral direction during the swing phase
Toe-in/toe-out angle	Average adduction/abduction angle during the swing phase
Roll angle of heel contact	Plantar roll angle when the heel touches the ground
Roll angle of toe-off	Plantar roll angle when the toe leaves the ground
Cadence	Number of steps per minute
Stance time	Amount of time that the foot is on the ground during the gait cycle
Swing time	Amount of time that the foot is off the ground during the gait cycle
Pushing time	Time between the heel lift and toe leaving the ground
Peak swing angular velocity	Peak angular velocity of the foot during the swing phase
Maximum speed during swinging phase	Maximum forward speed of the swinging leg during the swing phase
Foot clearance	Maximum heel height of the foot trajectory

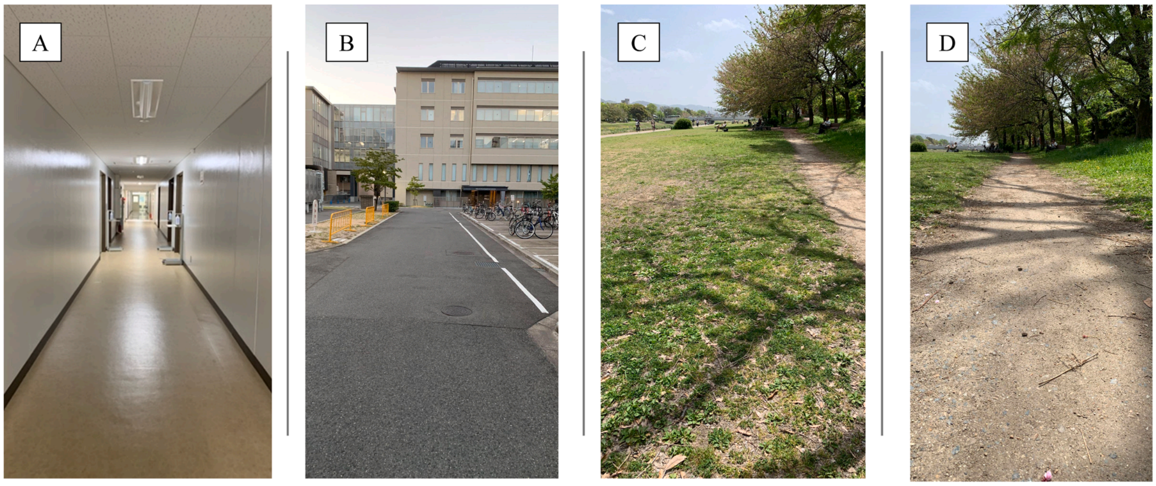

Fig. 1. (A) A. Laboratory corridor; (B) Asphalt, (C) Dirt, (D) Grass.

data were analyzed using repeated measures ANOVA. We first checked the assumption of sphericity for the repeated-measures ANOVA using-Mauchly's test of sphericity [21]. If Mauchly's test indicated that the assumption of sphericity was met ($P \geq 0.05$), we proceeded with the standard repeated measures ANOVA. However, if Mauchly's test violated the sphericity assumption ($P < 0.05$), we applied the Greenhouse-Geisser correction to adjust the degrees of freedom for the F-tests. Significant differences between conditions were explored using a post hoc test with Bonferroni corrections. Non-parametric data were analyzed using the Friedman test, and significant differences were examined using the Bonferroni post-hoc test. To examine the interaction between sex and surface type on gait parameters, a two-way repeated-measures ANOVA was conducted. In this analysis, sex was treated as a between-subject factor and surface type as a within-subject factor. The potential effects of sex, surface type, and their interaction were evaluated, and partial η^2 was calculated as an effect size for all main and interaction effects. The significance level was set at $P < 0.05$.

3. Results

Table 2 shows the characteristics of the study participants. The study analyzed data from 27 participants, consisting of 10 males and 17 females. The average age, height, weight, and Body Mass Index (BMI) of the participants was 21.1 years, 164.4 cm, 57.3 kg, and 21.1 kg/m^2, respectively. No dropout or adverse events were reported during the study period.

Table 3 presents the gait parameters measured over six minutes across the four different surface types: laboratory, asphalt, dirt, and grass. This table provides the mean and standard deviation (SD) of various gait parameters. The foot height was highest on grass (17.38 ± 1.59 cm) compared to other surfaces. The roll angle of heel contact showed a decreasing trend from the laboratory surface (5.66 ± 5.43°) to the grass (3.17 ± 5.12°). Stance time was relatively consistent across surfaces, with slight variations, ranging from 0.61 ± 0.04 s on dirt to 0.63 ± 0.04 s on laboratory and grass. Similarly, swing time showed minimal variation, ranging from 0.40 ± 0.01 s in the laboratory to 0.41 ± 0.01 s on dirt and grass. Heel clearance was highest on grass (25.77 ± 2.01 cm) and lowest in the laboratory setting (24.67 ± 1.97 cm), indicating differences in foot elevation between surfaces.

Table 4 presents the results of the repeated-measures ANOVA and Friedman test for various gait parameters across different surface types.

Table 2
Characteristics of the study participants ($n = 27$).

Characteristics	Mean ± SD
Age, years	21.1 ± 2.3
Height (cm)	164.4 ± 6.5
Weight (kg)	57.3 ± 9.3
BMI, kg/m^2	21.1 ± 2.3
Foot size	24.2 ± 1.4
	Frequency (%)
Sex	
Male	10 (37.0)
Female	17 (63.0)

BMI: body mass index (kg per m squared); SD: standard deviation.

Table 3
Mean and standard deviation of gait parameters on different surface types.

	gait on lab corridor	gait on asphalt	gait on dirt	gait on grass
	mean ± SD	mean ± SD	mean ± SD	mean ± SD
Walking speed (km/h)	5.07 ± 0.59	5.26 ± 0.75	5.26 ± 0.58	5.16 ± 0.56
Stride length (cm)	144.02 ± 14.80	148.22 ± 17.64	147.31 ± 14.65	148.44 ± 12.59
Maximum (peak) dorsiflexion angle (degree)	29.97 ± 5.10	31.20 ± 4.96	30.61 ± 4.22	29.37 ± 3.55
Maximum (peak) plantar flexion angle (degree)	77.79 ± 6.15	78.92 ± 10.20	78.84 ± 5.80	78.04 ± 6.29
Foot height (cm)	16.13 ± 1.55	16.44 ± 2.25	16.43 ± 2.02	17.38 ± 1.59
Circumduction (cm)	3.72 ± 1.72	3.64 ± 2.03	3.38 ± 1.39	3.45 ± 2.29
Toe-in/toe-out angle (degree)	11.84 ± 7.00	12.54 ± 6.45	12.36 ± 6.59	11.55 ± 6.23
Roll angle of heel contact (degree)	5.66 ± 5.43	4.55 ± 4.89	4.33 ± 5.37	3.17 ± 5.12
Roll angle of toe-off (degree)	−1.44 ± 3.97	−0.52 ± 3.53	−0.73 ± 3.67	−0.89 ± 2.82
Cadence (steps/min)	116.52 ± 4.54	117.34 ± 5.76	118.33 ± 4.87	115.10 ± 5.65
Stance time (s)	0.63 ± 0.03	0.62 ± 0.05	0.61 ± 0.04	0.63 ± 0.04
Swing time (s)	0.403 ± 0.012	0.404 ± 0.016	0.406 ± 0.012	0.415 ± 0.014
Pushing time (s)	0.20 ± 0.02	0.20 ± 0.02	0.19 ± 0.02	0.20 ± 0.02
Peak swing angular velocity (degree/s)	557.37 ± 72.70	572.91 ± 87.15	582.36 ± 74.59	567.16 ± 84.49
Maximum speed during swinging phase (km/h)	16.11 ± 1.38	16.50 ± 1.72	16.23 ± 1.32	16.10 ± 1.09
Heel clearance (cm)	24.67 ± 1.97	24.94 ± 3.16	24.97 ± 2.48	25.77 ± 2.01

Table 4
Comparison of gait parameters between different surface types.

	Repeated measures ANOVA			Friedman test	Significances
	Mauchly's test	Sphericity assumption	Greenhouse-Geisser correction		
Walking speed (km/h)	0.407	0.099			
Stride length (cm)	0.412	0.151			
Maximum (peak) dorsiflexion angle (degree)	0.074	0.102			
Maximum (peak) plantar flexion angle (degree)	<0.001		0.647		
Foot height (cm)				<0.001	*
Circumduction (cm)				0.77	
Toe-in/toe-out angle (degree)				0.123	
Roll angle of heel contact (degree)				0.004	*
Roll angle of toe-off (degree)				0.412	
Cadence (steps/min)	0.465	<0.001			*
Stance time (s)	0.766	<0.001			*
Swing time (s)	0.011		<0.001		*
Pushing time (s)	0.099	0.006			*
Peak swing angular velocity (degree/s)				<0.001	*
Maximum speed during swinging phase (km/h)	0.302	0.426			
Heel clearance (cm)				<0.001	*

The following parameters showed significant differences:

Regarding the spatial parameters, significant differences were found in foot height ($P< 0.001$), roll angle of heel contact ($P= 0.004$), and heel clearance ($P< 0.001$) across different surfaces.

Concerning the temporal parameters, significant differences were observed in cadence, stance time, swing time, and pushing time. Repeated-measures ANOVA showed significant differences in cadence ($P< 0.001$), stance time ($P< 0.001$), swing time ($P< 0.001$ with Greenhouse-Geisser correction), and pushing time ($P= 0.006$) across the different surfaces.

For the spatiotemporal parameters, significant differences were observed in the peak swing angular velocity ($P< 0.001$).

Other gait parameters did not show significant differences across the surfaces, including walking speed, stride length, maximum dorsiflexion angle, and maximum plantar flexion angle.

Table 5 presents the post-hoc test results for the significant gait parameters identified in the repeated-measures ANOVA and Friedman test, comparing the different surface types: laboratory, asphalt, dirt, and grass.

Table 5
Post hoc test results.

	lab vs asphalt	lab vs dirt	lab vs grass	asphalt vs dirt	asphalt vs grass	dirt vs grass
Bonferroni	P-value	P-value	P-value	P-value	P-value	P-value
Foot height (cm)	0.019	0.178	<0.001	1	0.137	0.014
Roll angle of heel contact (degree)	0.375	0.037	0.003	1	0.652	1
Cadence (steps/min)	1	0.047	0.218	0.842	0.007	<0.001
Stance time (s)	1	0.004	1	0.209	0.464	0.001
Swing time (s)	1	1	<0.001	1	<0.001	<0.001
Pushing time (s)	1	0.143	1	0.544	0.402	0.004
Peak swing angular velocity (degree/s)	0.011	0.001	1	1	0.078	0.011
Heel clearance (cm)	0.016	0.137	<0.001	1	0.586	0.104

3.1. Comparison with laboratory surface

For the spatial parameters, significant differences were observed in foot height, and heel clearance between the laboratory surface and grass ($P< 0.001$). The roll angle of the heel contact was significantly lower on the grass surface than on the laboratory surface ($P= 0.003$).

Significant differences were noted in the stance, swing, and pushing times regarding the temporal parameters. The stance time differed significantly between the laboratory and dirt surfaces ($P= 0.004$). The swing time was significantly longer on the grass than on the laboratory surface ($P< 0.001$). The pushing time was not significantly different between the laboratory and the other surfaces.

3.2. Comparison among asphalt, dirt, and grass surfaces

Regarding spatial parameters, significant differences in foot height were found between dirt and grass surfaces ($P= 0.014$).

Concerning temporal parameters, the stance and swing times demonstrated significant differences between the three surfaces. Significant differences were observed in cadence between asphalt and grass ($P= 0.007$) and between dirt and grass ($P< 0.001$). The stance time was also significantly different between dirt and grass surfaces ($P< 0.001$). The swing time and pushing time were significantly different between asphalt and grass ($P< 0.001$ and $P= 0.003$, respectively) and between dirt and grass ($P< 0.001$ and $P= 0.004$, respectively).

Table 6 presents the mean and standard deviation of the gait parameters for males and females under different surface conditions. Foot height, toe-in/out angle, and heel clearance notably differed between sexes. Specifically, foot height on grass was the highest for both males and females, with males exhibiting slightly higher values overall.

Table 7 presents the results, showing that no significant interaction effects between sex and surface type were observed for any of the analyzed parameters. However, significant main effects of sex were identified for foot height ($F= 19.656$, $p< 0.001$, partial $\eta^2 = 0.159$), toe-in/out angle ($F= 7.440$, $p= 0.007$, partial $\eta^2 = 0.067$), and heel clearance ($F= 25.372$, $p< 0.001$, partial $\eta^2 = 0.196$). This suggests that the effect of sex on gait dynamics remains consistent regardless of the surface type.

4. Discussion

4.1. Summary of findings

This study investigated the gait parameters of healthy adults while walking on four different surfaces: an indoor laboratory corridor, outdoor asphalt, outdoor dirt, and outdoor grass. The primary aim of this

Table 6
Mean and standard deviation of gait parameters by sex across surface conditions.

	Sex	Lab (Mean ± SD)	Paved (Mean ± SD)	Dirt (Mean ± SD)	Grass (Mean ± SD)
Walking speed (km/h)	Male	4.98 ± 0.51	5.23 ± 0.48	5.22 ± 0.47	5.12 ± 0.43
	Female	5.12 ± 0.66	5.28 ± 0.9	5.29 ± 0.67	5.19 ± 0.65
Stride length (cm)	Male	142.18 ± 13.12	148.49 ± 12.71	147.76 ± 12.69	148.96 ± 11.4
	Female	145.04 ± 16.33	148.07 ± 20.67	147.06 ± 16.38	148.16 ± 13.85
Maximum (peak) dorsiflexion angle (degree)	Male	28.75 ± 4.48	30.24 ± 3.91	30.04 ± 3.63	29.28 ± 3.26
	Female	30.64 ± 5.56	31.73 ± 5.62	30.92 ± 4.7	29.42 ± 3.89
Maximum (peak) plantar flexion angle (degree)	Male	75.76 ± 4.94	79.51 ± 2.92	77.28 ± 4.91	76.77 ± 5.60
	Female	78.92 ± 6.75	78.59 ± 12.91	79.71 ± 6.36	78.75 ± 6.87
Foot height (cm)	Male	16.92 ± 1.09	17.57 ± 1.10	17.65 ± 1.40	18.24 ± 1.22
	Female	15.69 ± 1.66	15.81 ± 2.55	15.75 ± 2.08	16.91 ± 1.65
Circumduction (cm)	Male	3.72 ± 1.50	3.35 ± 1.51	3.23 ± 1.53	2.52 ± 1.21
	Female	3.72 ± 1.92	3.8 ± 2.35	3.46 ± 1.39	3.96 ± 2.67
Toe-in/out angle (degree)	Male	14.91 ± 4.70	14.47 ± 5.07	14.82 ± 3.82	13.2 ± 4.10
	Female	10.14 ± 7.77	11.47 ± 7.17	11 ± 7.64	10.64 ± 7.25
Roll angle of heel contact (degree)	Male	8.45 ± 3.80	5.93 ± 2.77	6.75 ± 3.25	6 ± 4.57
	Female	4.11 ± 5.82	3.79 ± 5.80	2.99 ± 6.05	1.6 ± 4.98
Roll angle of toe-off (degree)	Male	−1.16 ± 3.79	−0.45 ± 3.08	−1.47 ± 3.28	−2.03 ± 2.74
	Female	−1.6 ± 4.27	−0.56 ± 3.93	−0.31 ± 4.0	−0.25 ± 2.81
Cadence (steps/min)	Male	115.86 ± 2.65	116.39 ± 2.99	116.97 ± 3.18	113.72 ± 2.64
	Female	116.88 ± 5.46	117.86 ± 7.0	119.08 ± 5.66	115.87 ± 6.87
Stance time (s)	Male	0.63 ± 0.02	0.62 ± 0.02	0.62 ± 0.03	0.64 ± 0.02
	Female	0.62 ± 0.04	0.61 ± 0.05	0.6 ± 0.04	0.62 ± 0.05
Swing time (s)	Male	0.4 ± 0.01	0.4 ± 0.01	0.4 ± 0.01	0.42 ± 0.01
	Female	0.4 ± 0.01	0.4 ± 0.02	0.41 ± 0.01	0.41 ± 0.02
Pushing time (s)	Male	0.2 ± 0.01	0.2 ± 0.01	0.2 ± 0.01	0.21 ± 0.02
	Female	0.2 ± 0.02	0.2 ± 0.03	0.19 ± 0.02	0.2 ± 0.03
Peak swing angular velocity (degree/s)	Male	539.38 ± 60.36	568.56 ± 58	560.87 ± 55.26	541.7 ± 65.11
	Female	567.36 ± 80.5	575.32 ± 103.5	594.3 ± 84.41	581.3 ± 94.45
Maximum speed during swinging phase (km/h)	Male	16.15 ± 1.10	16.56 ± 1.38	16.69 ± 1.28	16.31 ± 1.0
	Female	16.09 ± 1.58	16.47 ± 1.97	15.98 ± 1.33	15.98 ± 1.18
Heel clearance (cm)	Male	25.81 ± 1.40	26.68 ± 1.39	26.6 ± 1.62	27.06 ± 1.36
	Female	24.04 ± 2.04	23.97 ± 3.55	24.06 ± 2.51	25.05 ± 2.04

study was to evaluate and examine the effect of various walking surfaces on a wide range of gait parameters using IMUs. A comparison between the laboratory and outdoor surfaces revealed that foot height and heel clearance were higher on the outdoor surfaces, with significant differences observed between the laboratory and asphalt and between the laboratory and grass. The roll angle of the heel contact was lower on the

Table 7
Effects of sex and surface on gait parameters.

	Factor	F Value	P Value	Partial η^2 (Effect Size)
Walking speed	Intercept	6550.613	<0.001	0.984
	Sex	0.432	0.512	0.004
	Surface	0.592	0.622	0.017
	Sex × Surface (Interaction)	0.023	0.995	0.001
Stride length	Intercept	9155.988	<0.001	0.989
	Sex	0.006	0.94	0
	Surface	0.557	0.645	0.016
	Sex × Surface (Interaction)	0.082	0.97	0.002
Maximum (peak) dorsiflexion angle	Intercept	11,090.061	<0.001	0.991
	Sex	1.257	0.265	0.012
	Surface	0.263	0.852	0.008
	Sex × Surface (Interaction)	0.364	0.779	0.01
Maximum (peak) plantar flexion angle	Intercept	4360.739	<0.001	0.977
	Sex	1.445	0.232	0.014
	Surface	0.66	0.579	0.019
	Sex × Surface (Interaction)	0.174	0.914	0.005
Foot height	Intercept	9193.254	<0.001	0.989
	Sex	19.656	<0.001	0.159
	Surface	2.334	0.078	0.063
	Sex × Surface (Interaction)	0.214	0.887	0.006
Circumduction	Intercept	334.757	<0.001	0.763
	Sex	1.936	0.167	0.018
	Surface	0.326	0.807	0.009
	Sex × Surface (Interaction)	0.693	0.558	0.02
Toe-in/out angle	Intercept	376.321	<0.001	0.783
	Sex	7.44	0.007	0.067
	Surface	0.139	0.936	0.004
	Sex × Surface (Interaction)	0.139	0.936	0.004
Roll angle of heel contact	Intercept	98.145	<0.001	0.486
	Sex	13.409	<0.001	0.114
	Surface	1.037	0.379	0.029
	Sex × Surface (Interaction)	0.279	0.841	0.008
Roll angle of toe-off	Intercept	7.539	0.007	0.068
	Sex	0.701	0.404	0.007
	Surface	0.276	0.842	0.008
	Sex × Surface (Interaction)	0.538	0.657	0.015
Cadence	Intercept	48,719.447	<0.001	0.998
	Sex	2.56	0.113	0.024
	Surface	1.68	0.176	0.046
	Sex × Surface (Interaction)	0.066	0.978	0.002
Stance time	Intercept	23,171.502	<0.001	0.996
	Sex	2.912	0.091	0.027
	Surface	1.251	0.295	0.035
	Sex × Surface (Interaction)	0.072	0.975	0.002
Swing time	Intercept	91,453.454	<0.001	0.999
	Sex	0.068	0.794	0.001
	Surface	4.529	0.005	0.116
	Sex × Surface (Interaction)	0.363	0.78	0.01
Pushing time	Intercept	9174.946	<0.001	0.989
	Sex	2.092	0.151	0.02
	Surface	1.339	0.266	0.037
	Sex × Surface (Interaction)	0.102	0.959	0.003
Peak swing angular velocity	Intercept	4941.664	<0.001	0.979
	Sex	2.798	0.097	0.026
	Surface	0.449	0.719	0.013
	Sex × Surface (Interaction)	0.196	0.899	0.006

(*continued on next page*)

Table 7 (*continued*)

	Factor	F Value	P Value	Partial η^2 (Effect Size)
Maximum speed during swinging phase	Intercept	13,244.087	<0.001	0.992
	Sex	1.127	0.291	0.011
	Surface	0.423	0.737	0.012
	Sex × Surface (Interaction)	0.286	0.835	0.008
Heel clearance	Intercept	12,848.3994	<0.001	0.992
	Sex	25.372	<0.001	0.196
	Surface	1.114	0.347	0.031
	Sex × Surface (Interaction)	0.24	0.868	0.007

outdoor surfaces, with significant differences between the laboratory surface and the grass. The swing time tends to be longer on the outdoor surfaces, with significant differences between the laboratory and the grass. Among the outdoor surfaces, grass showed higher foot height, cadence, stance time, and swing time than dirt and asphalt. Our hypothesis stated that, compared with indoor walking, outdoor walking would exhibit larger spatial parameters, such as joint angles, and slower temporal parameters, such as walking speed and stance time. Among the outdoor surfaces, we expected the effects to be more pronounced in the order asphalt < dirt < grass, with grass showing the most significant deviation owing to its uneven nature. These results partially supported our hypothesis. As hypothesized, outdoor walking showed higher spatial parameters, specifically foot height and heel clearance, than indoor walking. In addition, the roll angle of the heel contact was lower on outdoor surfaces, particularly grass, which aligns with our prediction of greater deviations on uneven surfaces. Temporal parameters, such as swing time, were also longer on outdoor surfaces, especially on grass, supporting our hypothesis. However, our hypothesis that walking speed and stance time would be slower on outdoor surfaces than on indoor surfaces was not fully supported. Although the stance time showed some differences, the walking speed did not exhibit significant deviations across the surfaces. Thus, the hypothesis was validated, confirming several aspects; however, some elements were not fully supported by the data.

4.2. Novelty and significance of using IMS

One of the fundamental innovations of this study is the comprehensive measurement of clinically important gait parameters using IMUs. IMUs can measure a wide range of gait parameters and allow accurate and continuous movement tracking in real-world environments, thereby facilitating a comprehensive understanding of gait dynamics across different surfaces. In a previous study, IMUs were attached to the waist, thighs, and shanks to measure the gait on paved roads, sidewalks, cobblestones, grass, and inclines [22]. However, that study focused solely on the hip and knee joint movements, excluding the foot from the analyses. In contrast, the present study utilized IMUs to collect a variety of detailed gait parameters in outdoor environments and observed significant differences in foot-related parameters, such as foot height and heel clearance. Additionally, we found significant differences in the roll angle of the heel contact, which has not been previously evaluated. Moreover, temporal parameters such as cadence, stance time, and swing time also showed significant differences. Thus, the use of IMUs to measure a wide range of parameters enhances the significance of the study by better reflecting real-life conditions.

Another innovative aspect of this study was the use of an IMU system capable of long-duration measurements. The IMU used in this study was a thin device inserted into a dedicated insole, requiring no special operation from the participants once installed. This allows for continuous, long-term measurements in daily life without the need for specific instructions or interventions [23]. Moreover, this capability makes the system particularly applicable to long-term evaluations of populations with medical conditions. Our findings contribute to a deeper understanding of the factors that influence gait dynamics in daily life and offer valuable insights for interpreting data from future long-term evaluations.

4.3. Interpretation of results

The observed significant increases in foot height, stance time, and swing time, as well as the significant decrease in cadence while walking on grass, can be interpreted as consistent, interrelated changes. With the increase in foot height without changes in other parameters, such as stride length, the trajectory of the foot during the swing phase may be extended, leading to an increased swing time. Additionally, cadence is calculated from the number of steps per minute; therefore, if the stance and swing time increase, the number of steps per minute decreases, resulting in a lower cadence. A previous study also confirmed that compared to other environments, walking on grass increases the energy cost of walking and reduces walking efficiency; similar trends were observed in this study [8].

These results can be attributed to several factors. The significant increase in foot height and swing time may be because the height of the grass obstructs the forward foot movement during the swing phase, thus increasing the risk of tripping and falling, necessitating a higher foot lift to avoid these obstacles. Uneven surfaces were associated with an increased risk of tripping [24] and foot height [25], and we observed similar trends on the grass surfaces in this study.

The extension of stance time and decreased cadence may also be from efforts to improve walking stability on uneven surfaces. A previous study conducted on treadmills in laboratory settings has reported that ankle inversion and eversion angle changes and muscle activity increase around the ankle are necessary to maintain balance on irregular surfaces, leading to a reduction in walking speed [2]. Although we did not observe a significant decrease in walking speed in this study, there was a trend towards slower walking on grass in the outdoor environment and a confirmed significant reduction in the roll angle of the heel contact, indicating ankle eversion. These findings suggest that the participants may have been adjusting their gait to maintain balance on an uneven grass surface, consistent with previous research [2,26,27]

In a previous study, walking on unstable rocky surfaces decreased walking speed and stride length while showing larger external rotation of the ankle on unstable surfaces [28]. However, this tendency was not observed in the present study. The differences in the results could be attributed to several factors: previous studies compared flat surfaces, urethane mats, and unstable rocky surfaces, whereas this study compared laboratory corridors, paved roads, dirt, and grass; previous studies simulated various environments in a laboratory setting, whereas this study used real outdoor environments; and previous studies employed motion capture cameras and pressure measurement systems, whereas this study utilized IMUs. These methodological and environmental differences may have influenced the trends observed in our results.

Furthermore, this study found significant main effects of sex on foot height, toe-in/out angle, and heel clearance; however, no interaction effects between sex and surface type were observed for any gait parameter. These results suggest that while sex significantly influences specific spatial gait parameters, this influence does not vary across different surface conditions. The absence of interaction effects indicates that the effect of sex on these parameters remains consistent regardless of the walking surface.

4.4. Limitations

This study had several limitations. The sample consisted solely of young adults, limiting the generalizability of the findings to older adults or those with walking impairments. This study did not measure electromyography (EMG) or confirm whether these trends were more pronounced in older adults with a higher risk of falling; therefore, strong conclusions cannot be drawn. Additionally, the measurements were conducted under dry weather conditions, preventing assessing the impact of wet or slippery conditions on the gait parameters.

4.5. Future research directions

Future studies should include a broader range of participants, such as older adults and individuals with mobility impairment, to better understand how different populations adapt to various walking surfaces. Research under different weather conditions, such as rain or snow, would also provide a more definitive understanding of how environmental factors influence gait. Long-term data collection using IMS can reveal variations in walking patterns over time and under different daily conditions.

4.6. Practical applications

The results of this study provide practical insights for designing rehabilitation and exercise programs. Ankle sprains and chronic ankle instability can restrict ranges of motion during ankle inversion and eversion [29,30]. Monitoring the roll angle of the heel contact while walking on uneven surfaces, such as grass, using IMUs can help compare injured and noninjured limbs. This approach facilitates the evaluation of whether functional recovery extends to activities of daily living and enables training tailored to real-world conditions. Walking training on various surfaces can enhance functional recovery in patients with spinal cord injury [30]. By incorporating surfaces such as grass and other uneven terrains into training programs and monitoring improvements in foot height, toe-in/out angle, and roll angle of heel contact, therapists can use these parameters as indicators to improve balance and stability.

Furthermore, the application of IMUs in real-time feedback systems is a promising avenue for enhancing rehabilitation outcomes. Providing immediate feedback on gait parameters such as the roll angle of heel contact, foot height, and heel clearance enables users to adjust their walking patterns, improve stability, and reduce fall risk. For instance, wearable IMU systems can alert users when their gait deviates from the recorded daily walking patterns, prompting corrective actions. This could be particularly beneficial for older adults or individuals recovering from lower limb injuries.

Finally, these findings support physical therapists and exercise professionals in creating more effective and diverse training environments that mimic real-world walking conditions. The use of IMUs in daily settings offers valuable long-term and real-time feedback for monitoring and improving gait, thereby reducing the risk of falls and enhancing overall mobility.

5. Conclusion

Walking on grass significantly alters gait parameters, increasing foot height, swing time, and roll angle of the heel contact. These changes were likely due to the high and uneven nature of grass surfaces. The use of IMUs in this study provided detailed real-world gait data. Understanding these differences is crucial for developing strategies for improving walking stability and preventing falls in various environments.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this study, the authors used ChatGPT4/OpenAI to improve language and readability. After using this tool/service, the authors reviewed and edited the content as required and took full responsibility for the publication.

Data statement

The data dataset generated during the current study are available from the corresponding author upon reasonable request, after approval by the data access committee.

Ethical approval

The study received approval from the Ethics Committee of the Graduate School and Faculty of Medicine, Kyoto University (approval no R3664–3).

CRediT authorship contribution statement

Hiroki Shimizu: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Kyoma Tanigawa:** Conceptualization, Methodology, Investigation, Methodology, Writing – review & editing. **Anuradhi Bandara:** Conceptualization, Methodology, Investigation, Methodology, Writing – review & editing. **Shinichi Kawamoto:** Conceptualization, Methodology, Investigation, Methodology, Writing – review & editing. **Shota Suzuki:** Conceptualization, Methodology, Investigation, Methodology, Writing – review & editing. **Momoko Nagai-Tanima:** Supervision, Project administration, Writing – review & editing. **Tomoki Aoyama:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Tomoki Aoyama reports equipment, drugs, or supplies was provided by NEC Corporation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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