The impact of outdoor walking surfaces on lower-limb coordination and variability during gait in healthy adults.

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Abstract.

Background: Inter-joint coordination and variability during gait provide insight into control and adaptability of the neuromuscular system. To date, coordination research has been restricted to laboratory settings, and it is unclear how these findings translate to real-world, outdoor walking environments.
Research Question: Compared to flat walking, to what extent do outdoor surfaces impact lower-limb inter-joint coordination and variability during gait, in healthy adults?
Methods: Data from inertial measurement units placed on the lower-back, thigh, and shank were extracted from thirty healthy young adults (15 females, 23.5 ± 4.2 years) during outdoor walking on flat (paved sidewalk); irregular (cobblestone, grass); sloped (slope-up, slope-down); and banked (banked-right, banked-left) surfaces. Sagittal joint angles for the right knee and hip were computed and partitioned by gait phase (stance and swing). Continuous Relative Phase analysis determined inter-joint coordination and variability for the knee-hip joint pair using Mean Absolute Relative Phase (MARP) and Deviation Phase (DP), respectively. One-way repeated measures ANOVAs tested surface effects. Post-hoc Bonferroni adjusted surface comparisons were assessed.
Results: Significant knee-hip surface effects were seen during all gait phases for MARP ($p < 0.001$) and DP ($p \leq 0.001$). Compared to flat walking, grass prompted more in-phase coordination (smaller MARP) during stance and swing phase ($p \leq 0.003$). Slope-up caused more in-phase coordination during stance ($p < 0.001$), while slope-down caused more out-of-phase coordination during stance and swing ($p \leq 0.003$), compared to the flat surface. Sloped surfaces prompted more variable (larger DP) knee-hip coordination ($p \leq 0.001$), compared to flat walking during stance and swing phase.
Significance: Compared to flat walking, changes in knee-hip coordination and variability were greatest on slope-up/slope-down surfaces. This could reflect greater changes in lower-limb kinematics on sloped surfaces and/or a neuromuscular response to the demands of a more challenging task.

Introduction

Walking on diverse surfaces represents an everyday task for healthy adults. These surfaces could include irregular terrains, slopes, or banked (cross-slopes) walkways. While research demonstrates that these surfaces prompt changes in gait kinematics [1-3]; regrettably, few studies investigate the impact of walking surfaces on lower-limb coordination and variability. By examining movement coordination and its variability, we may discern neuromuscular control and adaptability of the motor system [4].

Continuous Relative Phase (CRP) is an analytical approach which quantifies inter-joint coordination by describing phase relationships between two body segments or joints [5, 6]. Specifically, changes in coordinative variability in response to task demands can point to more rigid or unstable movement behavior [7]. In turn, these neuromuscular control changes could have implications for musculoskeletal injury [8]. In gait research, changes in lower-limb coordination and variability have been studied from the perspective of gait speed [9], asymmetrical leg loading [10], obstacle crossing [11], and to a lesser extent, walking surfaces [12]. The latter are of particular interest because they replicate the challenges of navigating real-world walking environments and can increase sensitivity in identifying age-related gait changes [12, 13]. Recent work observed more in-phase and variable Knee-Hip coordination on irregular, compared to flat, surfaces, with changes in coordination being accentuated in older adults during early stance phase [12]. Others reported more out-of-phase and variable thigh-shank coupling in healthy adults while walking on a negative treadmill incline [14]. While these findings suggest that challenging surfaces influence gait coordination, these studies have been limited to laboratory settings, and it is unclear how findings translate to real-world walking environments.

Recent advances in wearable sensor technologies, such as inertial measurement units (IMUs), permit gait analysis in outdoor environments [15]. This allows the study of gait coordination and variability in the real-world and increases the ecological validity of findings. Such data will provide insight into how coordination strategies change in response to differing surfaces encountered during everyday locomotion, and serve as normative findings to inform future research. Therefore, the purpose of this study was to determine the impact of outdoor walking surfaces on lower limb inter-joint coordination and variability during gait, in healthy adults. We hypothesized that irregular, sloped, and banked surfaces would induce changes in coordination and variability in Knee-Hip joint coupling during gait, in comparison with flat walking.

1. Methods

1.1. *Participants*

Thirty healthy young adults (15 females, 23.5 ± 4.2 years, 169.3 ± 21.5 cm, 70.9 ± 13.9 kg) were recruited from Northeastern University (Boston, USA). Participants provided written consent and study procedures were approved by Harvard and Northeastern Institutional Review Boards. Additional demographic details are provided in a previously published manuscript [15].

1.2. *Data Collection*

Participants were fit with six IMUs (MTw Awinda, Xsens, Enschede, Netherlands). For this study, data from the pelvis (L5/S1), right thigh (anterior), and right shank (5 cm above the bony process of the ankle) were extracted for the following surfaces: (1) flat; (2) uneven cobblestone; (3) grass; (4) banked-left; (5) banked-right; (6) sloped-up; and (7) sloped-down (Figure 1). Sloped-up and -down is an Americans with Disabilities Act (ADA) compliant ramp with a slope of 4-5 degrees (8.33% incline). The stairs have 6 inch rise and 14 inch run. The cobblestone pavers were 10-11 inches long and 7 inches wide with the longer length in line with the walking direction. The pavers were 1/4 to 1/2 inch apart. Peak-to-peak of the paver vertical service is 2/5 inches. Grass surface was approximately 1.5 inches tall; however, as data were collected over multiple days, height may have varied. Surfaces were categorized as: irregular (uneven cobblestone, grass); sloped (slope-up, slope-down); and banked (banked-right, banked-left). Banked-right refers to the limb on the higher end of the slope, while banked-left refers to the limb on the lower end of the slope.

Participants performed six walking trials on each surface, at self-selected speeds. Surface order was randomised. For flat, grass, and uneven cobblestone surfaces, participants changed walking direction on alternate trials.

1.3. Data processing and analyses

Data were collected using MT software (Xsens, Enschede, Netherlands), sampled at 100 Hz. Sensor data were synchronized and exported to .txt files. Next, data were imported to MATLAB (R2019a, The MathWorks, Natick, USA) and smoothed using a 2nd order Butterworth low pass filter (6Hz cut-off). Gait cycles were delimited via heel-strikes using the magnitude of angular velocity of the shank IMU [16] (Supplemental Figure 1).

Joint angles were computed based on the Xsens MVN algorithm [17]. The sensor fusion algorithm combines acceleration, angular velocity, and magnetism data to estimate quaternion sensor orientations [18]. Quaternion orientations were converted to Euler angles in the ZYX axis rotation sequence [17, 19]. Resulting pitch angles represent rotation about the Y-axis and characterize sagittal plane joint angles. Knee angles were expressed with respect to the anatomical static standing position. Hip angles did not require correction as static posture flexion was approximately 0° (Supplemental Figure 2). Lastly, sagittal hip and knee joint angle data for three consecutive gait cycles were extracted from each trial.

Continuous Relative Phase (CRP) analysis described lower-limb inter-joint coordination and variability [5]. The first and third gait cycles served as data pads (i.e. extraneous data) to help manage edge-effects associated with CRP analyses [20]. Phase angles for the hip and knee joints were determined using the Hilbert-transform method [6, 21] and evaluated for six trials, on all seven walking surfaces, for all participants. Next, data pads were removed, leaving one full gait cycle per trial for analyses. The absolute difference between knee and hip phase angles determined the CRP relationship for the Knee-Hip joint pair. CRP values exceeding 180° were subtracted from 360° to manage discontinuities in data [6], restricting CRP values to a scale from 0° (fully in-phase) to 180° (fully out-of-phase). Separate CRP curves were time normalized to 100% of the gait cycle, and subdivided into stance and swing based on normative gait event timings [22]. The

Mean Absolute Relative Phase (MARP) quantified CRP amplitude by taking the average of the ensemble curve for each gait phase [23]. The Deviation Phase (DP) quantified within-individual CRP variability by averaging the standard deviations of the ensemble CRP curves, for each gait phase [23]. This was repeated for the Knee-Hip joint pair in all participants, on all walking surfaces. Mathematical details of our CRP implementation were described previously [12].

1.4. Statistical Analyses

One-way repeated measures analysis of variance (1 × 7 ANOVAs) tested our hypothesis that Knee-Hip inter-joint coordination during gait differed across surface types. Walking surface was our within-subject factor (flat, cobblestone, grass, banked-left, banked-right, slope-up, slope-down). Partial Eta-Squared (η^2) quantified effect sizes. Separate analyses were performed for our dependent variables (MARP, DP), for each gait phase (stance, swing). For each analysis, the assumption of sphericity was violated and a Greenhouse-Geisser correction was applied. Following significant main effects, post-hoc Bonferroni adjusted ($p \leq 0.006$) paired t-tests were performed for nine selected comparisons examining: (i) irregular surfaces (flat vs. grass; flat vs. cobblestone; grass vs. cobblestone); (ii) sloped surfaces (flat vs. slope-up; flat vs. slope-down; slope-up vs. slope-down); and (iii) banked surfaces (flat vs. banked-right; flat vs. banked-left; banked-right vs. banked-left). Normality was tested for the ANOVA main effects and post-hoc comparisons using the Shapiro-Wilkes test. If parametric assumptions were not met, Friedman ANOVA and Wilcoxon Signed-Rank tests were run instead of ANOVAs and paired t-tests, respectively (See Supplemental Table 1 for implemented tests). Cohen's d and Glass's delta (**Δ**) determined effect sizes for the results of the post-hoc paired t-tests and Wilcoxon Signed-Rank tests, respectively [24]. Level of significance was set at $\alpha \leq 0.05$. Statistical analyses were performed using SPSS (Version 23, IBM, Chicago, USA).

2. Results

Average hip and knee joint angles for flat, irregular, sloped, and banked surfaces are presented in Figure 2.

For the Knee-Hip joint pair, significant surface effects were seen during both gait phases for MARP ($p < 0.001$) and DP ($p \leq 0.001$). Group means (standard deviations) for MARP and medians (interquartile ranges) for DP are summarized in Table 1.

2.1. Inter-joint coordination (MARP) post-hoc comparisons

Irregular surfaces: Grass walking prompted more in-phase Knee-Hip coupling (smaller MARP) compared to a flat surface (stance and swing phases; $p \leq 0.003$, $d \geq 0.60$; Table 2, Figure 3) and cobblestone walking (stance phase; $p = 0.004$, $d = 0.57$). There were no statistical differences in MARP when walking on cobblestone, compared to flat surfaces ($p \geq 0.086$).

Sloped surfaces: Slope-down walking induced more out-of-phase coordination during gait as compared to flat (stance and swing phases; $p \leq 0.001$, $d \geq 0.86$; Table 2, Figure 3) and slope-up walking (stance and swing phases; $p \leq 0.003$, $d \geq 0.60$). Compared to flat, slope-up surfaces prompted more in-phase behavior during stance ($p < 0.001$, $d = 1.17$).

Banked surfaces: All comparisons between flat and banked surfaces were statistically insignificant ($p \geq 0.062$) (Table 2, Figure 3).

2.2. Inter-joint coordination variability (DP) post-hoc comparisons

Irregular surfaces: There were no statistical differences in Knee-Hip DP when comparing flat, grass, and cobblestone surfaces ($p \geq 0.12$; Table 2, Figure 4).

Sloped surfaces: Compared to flat surfaces, a more variable walking strategy was observed during gait for both slope-up (stance and swing phases; $p \leq 0.001$, $\boldsymbol{\Delta} \geq 1.46$; Table 2, Figure 4) and slope-down (stance and swing phases; $p \leq 0.001$, $\boldsymbol{\Delta} \geq 1.06$) walking conditions. There were no statistical differences in DP when comparing slope up and slope down walking surfaces ($p \geq 0.29$; Table 2, Figure 4).

Banked surfaces: No statistically significant differences were observed when comparing DP during walking on flat and banked surfaces ($p \geq 0.14$; Table 2, Figure 4).

3. Discussion

3.1. Summary

This study compared the effects of outdoor walking surfaces on Knee-Hip inter-joint coordination (MARP) and its variability (DP), in healthy adults. Our hypothesis was partially confirmed, as some, but not all, outdoor surfaces induced changes in coordination and variability. Compared to flat walking, the grass surface prompted more in-phase coupling during stance and swing phase. The slope-up surface caused more in-phase Knee-Hip coordination during stance, while the slope-down walkway resulted in more out-of-phase coupling during stance and swing. Both slope-up and slope-down walking conditions prompted more variable coordination strategies during stance and swing.

3.2. Changes in inter-joint coordination (MARP) on different walking surfaces

3.2.1. Irregular surfaces (grass, uneven cobblestone)

Compared to flat surfaces, grass prompted more in-phase Knee-Hip coupling during stance and swing phase. Irregular surfaces represent a more complex task for the neuromuscular system, and this observed change in coordination is likely adaptive; serving to help maintain upright stability during gait and reduce risk of falling [4]. Irregular surfaces change gait dynamics by inducing greater knee and hip flexion during stance, a response potentially aimed at lowering the center of mass to improve stability [13, 25]. Thus, more in-phase Knee-Hip coupling may characterize a stabilizing gait strategy. On the cobblestone surface, however, Knee-Hip MARP was not statistically different from flat walking. This suggests that different surfaces have distinct effects on lower-limb coordination during gait or that the cobblestone irregularities were not a significant challenge to our population.

Past work reported more in-phase Knee-Hip coordination on irregular, compared to flat brick surfaces, in healthy adults walking in a laboratory setting [12]. These findings were largely in-line with our results on grass (i.e. more in-phase); however, they differed from our observations during cobblestone walking. This is likely explained by the fact that the lab-based irregular brick setup was meant to reproduce an unmaintained brick surface with significant medio-lateral and antero-posterior height irregularities (c.f. [12] for more details). Otherwise, there is sparse work examining changes in inter-joint coordination during gait on irregular surfaces. Others have compared inter-joint coordination during treadmill and overground walking, finding no difference between the two [26]; however, a treadmill remains functionally different from an irregular, outdoor surface.

3.2.2. Sloped surfaces (slope-up, slope-down)

Compared to flat walking, a slope-up surface prompted more in-phase Knee-Hip coupling during stance, while a slope-down surface evoked more out-of-phase coupling during all of gait. Past work studying the impact of sloped surfaces on gait kinematics may help explain our findings. For instance, slope-up surfaces prompt changes towards greater hip, knee, and ankle flexion at heel strike, followed by greater extension at mid-stance [2]. This behavior reflects the need to increase toe clearance and propel the body upwards during uphill walking [2]. Considering that CRP is a measure of how in-sync two joints/segments move in relation to one another [5, 8], concurrent changes in flexion/extension should translate to more in-phase coupling – a behavior observed in the present study. In contrast, walking downhill requires greater knee flexion during stance, and is accompanied by a simultaneous reduction in hip extension [2, 3]. A transfer to a knee dominant strategy with a stiffening of hip motion would suggest less synchronous coupling, as observed herein. This knee-dominant strategy could reflect a controlled lowering of COM to maintain stability, as knee muscles are tasked with braking forward acceleration during downhill walking [27].

The sole study to examine the impact of sloped surfaces on lower-limb coordination using CRP analyses is partially consistent with ours, showing more out-of-phase thigh-shank coupling on a negative treadmill slope (-9°), in healthy adults [14]. In contrast, while we found more in-phase Knee-Hip coupling on an uphill slope, their findings did not support this notion.

3.2.3. Banked surfaces (banked-right, banked-left)

The banked surface did not evoke meaningful changes in Knee-Hip MARP during gait. There were no differences in joint coupling between the limb on the higher (banked-right), and lower (banked-left) ends of the slope. Banked, or cross-sloped surfaces induce asymmetrical changes in both limbs by causing greater hip, knee, and ankle joint flexion on the higher limb, with a concurrent decrease in joint flexion in the lower limb [1, 28]. While statistically significant, these kinematic changes in sagittal plane joint angles are small (e.g. < 5° change in knee flexion [1]), compared to changes observed during sloped-up/down walking (e.g. 15-40+ ° change [2]). It is possible that small kinematic changes observed on banked surfaces do not translate to meaningful changes in coordination, or that kinematic adaptations in the frontal plane are not picked up by sagittal plane CRP analyses. Perhaps a greater slope, capable of inducing greater kinematic changes (e.g. > 10°

[28]) would prompt an altered coordination strategy. To our knowledge, there are no comparable studies to better situate our findings.

3.3. Changes in inter-joint coordination variability (DP) on different walking surfaces

Compared to flat walking surfaces, irregular and banked surfaces had no significant impact on Knee-Hip coordinative variability during gait. Therefore, the following paragraphs will focus on sloped surfaces.

3.3.1. Sloped surfaces (Slope-up, Slope-down)

Compared to flat walking, both slope-up and slope-down surfaces prompted more variable Knee-Hip coordination across the gait cycle, with this effect being stronger during slope-up conditions. Coordinative variability provides insight into neuromuscular control, and a degree of variability allows "motor flexibility" when performing voluntary movement (e.g. walking) [8, 29]. Large changes in variability, however, can reflect unstable (i.e. excessive variability) or rigid (i.e. insufficient variability) movement patterns [8, 29]. When considering our healthy sample, the observed increase in variability is likely functional, and reflects a neuromuscular adaptation to a more challenging surface [30]. This is broadly consistent with others who observed changes in variability during gait in healthy individuals following an added challenge [10, 12]. While excessive changes in coordinative variability may become problematic during gait, particularly in older adults [31], the inflection point at which variability stops being functional and becomes problematic is difficult to define. It is, however, unlikely that this threshold was reached in our healthy sample.

Dewolf et al. [14] reported findings in-part consistent with ours, showing greater thigh-shank variability during downhill (at -6 and -9°inclines), but not uphill, walking. Again, these disparities may relate to differences in slope of the incline, or treadmill vs. outdoor environments. A lack of robust findings regarding changes in variability on irregular, compared to flat, surfaces is slightly surprising; especially since greater variability has been reported on irregular surfaces during gait, in healthy adults [12]. Again, the indoor irregular surface was more "irregular" than our outdoor walking surfaces.

3.4. Limitations

This work has certain limitations. First, findings cannot be extrapolated to older adults, or clinical populations; however, given the large amount of data analysed (> 90 gait cycles / surface), the results are robust for a young, healthy population. Further, lack of data on the ankle joint prevents generalizability to coordination of joint couples beyond the Knee-Hip pair. While our walking surfaces were meant to reflect 'typical' outdoor environments, we did systematically assess each possible category of walking surface. Due to the many possible variations in outdoor surfaces (e.g., grass length, slope inclines), our findings cannot be generalized to surfaces beyond those studied herein. Approaches to quantify surface irregularity via, for example, a roughness index, as presented by Thomas et al. [32] would allow for reproducibility of findings. Participants performed walking tasks at self-selected speeds; therefore, we cannot discount the potential influence of gait speed on our findings. We chose to report inter-joint coordination using joint angles rather than segment angles based on the former's familiarity to the gait community. It is possible that similar analyses using segment angles would have generated slightly different results.

4. Conclusion

Outdoor walking surfaces differentially impact Knee-Hip inter-joint coordination and variability. Compared to flat walking, more in-phase coupling was observed on grass and slope-up surfaces during stance, while more out-of-phase coupling occurred on slope-down during most of gait. Variability was greater on both slope-up and slope-down surfaces. These findings could reflect greater changes in lower-limb kinematics on sloped surfaces and/or a neuromuscular response to a more challenging walking surface.

Code and data associated with this investigation are available at:
https://github.com/PhilD001/crp_outdoor_surfaces

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Conflict of interest

None

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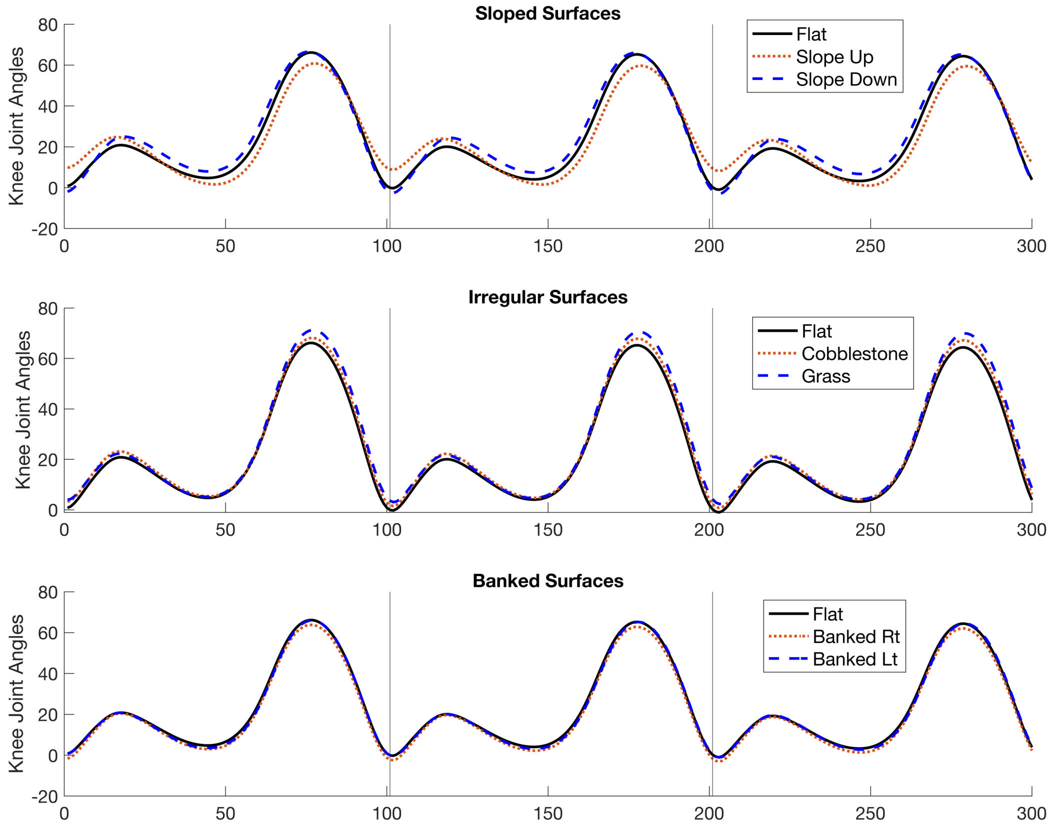
	Gait Phase	Surface							P-value	Effect size
		Flat	Grass	Cobble stone	Slope up	Slope down	Bank Right	Bank Left		
MARP	Stance	85.9 (7.3)	80.4 (8.6)	84.6 (6.2)	72.5 (9.6)	91.9 (8.0)	86.4 (8.3)	85.3 (6.7)	**<0.001**	0.562
	Swing	86.1 (9.1)	82.0 (7.5)	85.0 (7.1)	87.3 (7.0)	91.1 (8.8)	87.7 (8.9)	87.0 (7.6)	**<0.001**	0.347
DP	Stance	6.2 (3.3)	7.0 (3.2)	7.4 (3.6)	12.3 (6.8)	11.5 (6.1)	6.5 (4.4)	6.4 (3.4)	**<0.001**	0.429
	Swing	5.1 (2.9)	4.9 (1.8)	5.1 (2.6)	7.7 (5.2)	8.3 (3.0)	5.4 (2.5)	4.8 (2.0)	**<0.001**	0.375

Table 1. Mean (standard deviation) for Mean Absolute Relative Phase (MARP) and median (interquartile range) for Deviation Phase (DP) variables for the Knee-Hip joint pair during each phase of gait. Higher values indicate more out-of-phase joint coupling (MARP) and greater variability (DP). Surface effect p-values (p) and effect sizes (MARP: η^2; DP: Kendall's W) are shown, bolded indicates statistical significance of $p < 0.05$).

	Gait Phase	Flat vs. Grass	Flat vs. Cobble stone	Grass vs. Cobble stone	Flat vs. Slope up	Flat vs. Slope down	Slope up vs. Slope down	Flat vs. Bank R	Flat vs. Bank L	Bank R vs. Bank L
MARP	Stance	**0.001** (0.70)	0.086 (0.32)	**0.004** (0.57)	**<0.001** (1.17)	**<0.001** (0.86)	**<0.001** (1.98)	0.56 (0.11)	0.44 (0.14)	0.18 (0.25)
	Swing	**0.003** (0.60)	0.19 (0.26)	0.008 (0.53)	0.38 (0.52)	**<0.001** (1.28)	**0.003** (0.60)	0.062 (0.35)	0.20 (0.24)	0.33 (0.16)
DP	Stance	0.17 (0.035)	0.12 (0.13)	0.63 (0.10)	**<0.001** (1.67)	**<0.001** (1.21)	0.29 (0.46)	0.26 (0.20)	0.86 (0.072)	0.47 (0.27)
	Swing	0.70 (0.039)	0.41 (0.032)	0.12 (0.071)	**<0.001** (1.46)	**<0.001** (1.06)	0.81 (0.40)	0.41 (0.25)	0.89 (0.16)	0.14 (0.41)

Table 2. P-values (Cohen's d / Glass's delta) post-hoc Bonferroni corrected paired t-test and Wilcoxon Signed-Rank tests comparing Mean Absolute Relative Phase (MARP) and Deviation Phase (DP) values for the Knee-Hip joint pair between select walking surfaces. Bonferroni corrected α were set at ≤ 0.006.

Figure 1. Outdoor sites showing, from left to right, (a) flat, (b) sloped, (c), grass, (d) banked, (e) cobblestone brick surfaces.


Sloped Surfaces

Irregular Surfaces

Banked Surfaces

Figure 2A. Sagittal plane knee joint angles (degrees) across three gait cycles on sloped (slope-up, slope-down), irregular (cobblestone, grass), and banked (banked-right, banked-left) surfaces, compared to flat walking (solid black line). Vertical lines delineate separate gait cycles. Positive values indicate joint flexion.

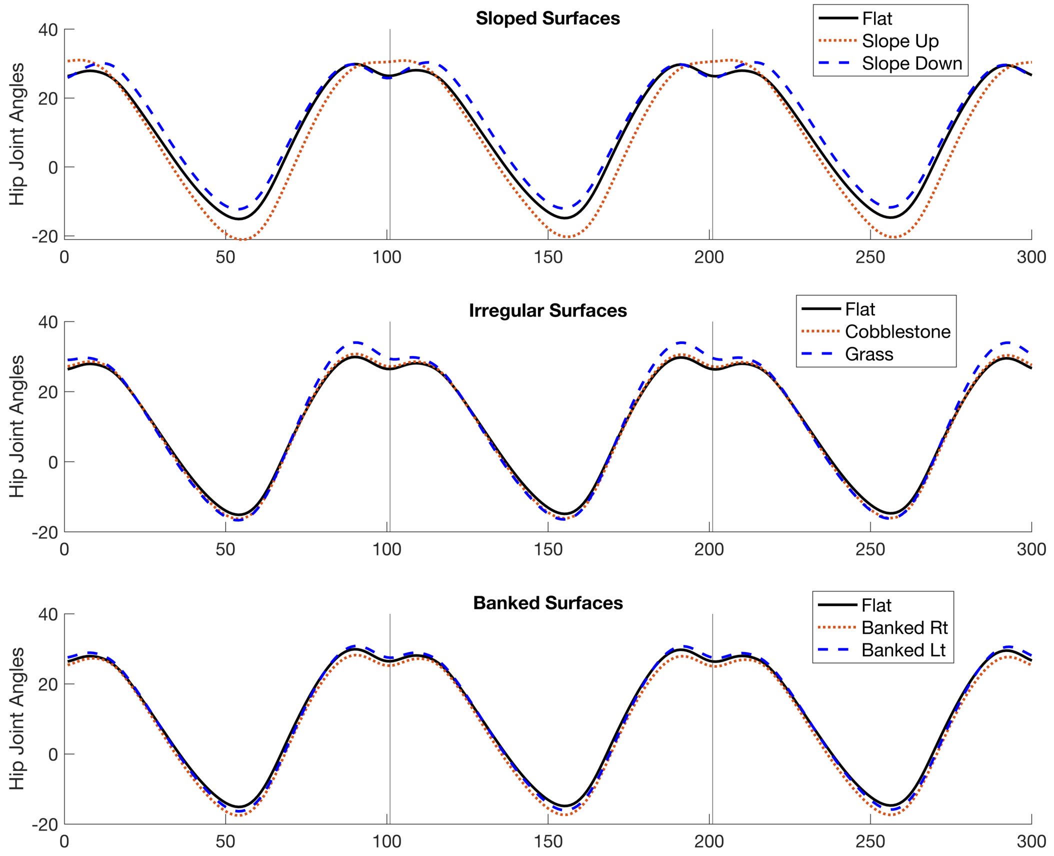


Figure 2B. Sagittal plane hip joint angles (degrees) across three gait cycles on sloped (slope-up, slope-down), irregular (cobblestone, grass), and banked (banked-right, banked-left) surfaces, compared to flat walking (solid black line). Vertical lines delineate separate gait cycles. Positive values indicate joint flexion.

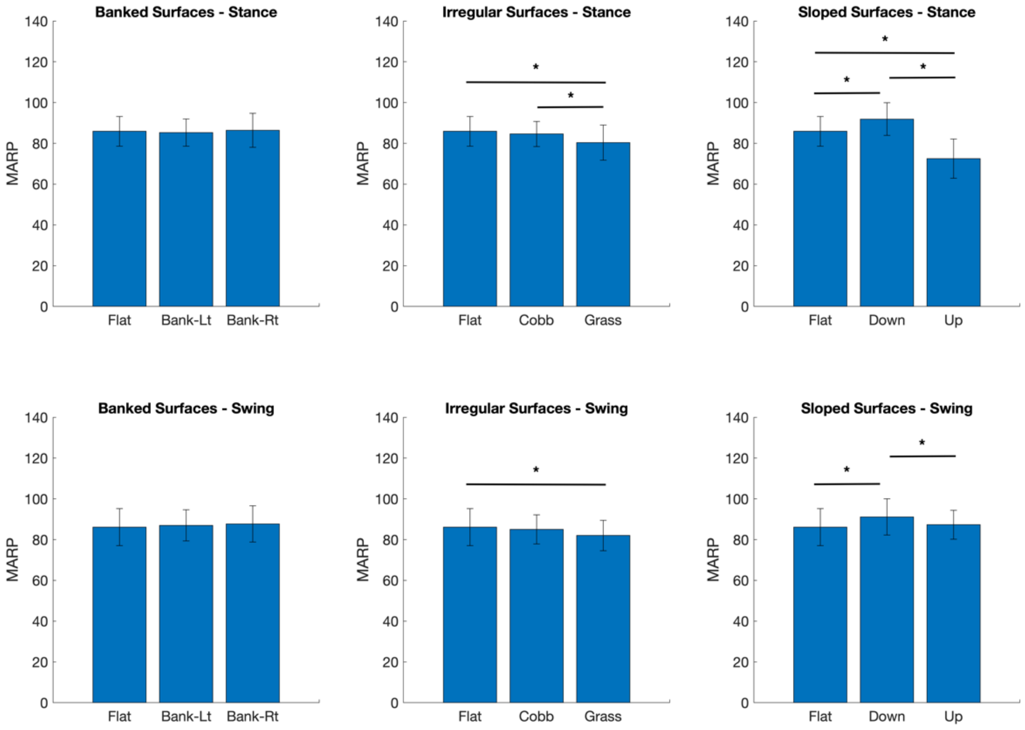


Figure 3. Knee-Hip Mean Absolute Relative Phase (MARP) means (standard deviations) on sloped, irregular, and banked surfaces during gait. Higher values indicate less in-phase joint coupling. Bank-Lt: Banked-left; Bank-Rt: Banked right; Cobb: Cobblestone; Down: Slope-Down; Up: Slope-Up. Asterisk denotes Bonferroni-adjusted statistically significant finding ($p \leq 0.006$). Top and bottom row show results for stance and swing, respectively.

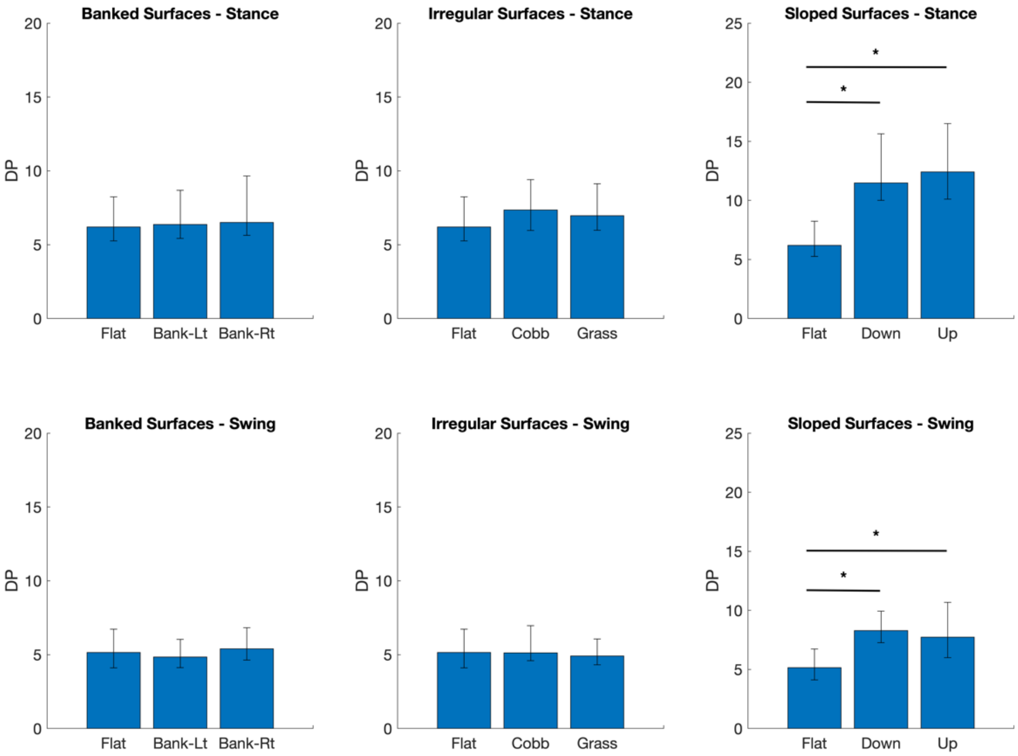
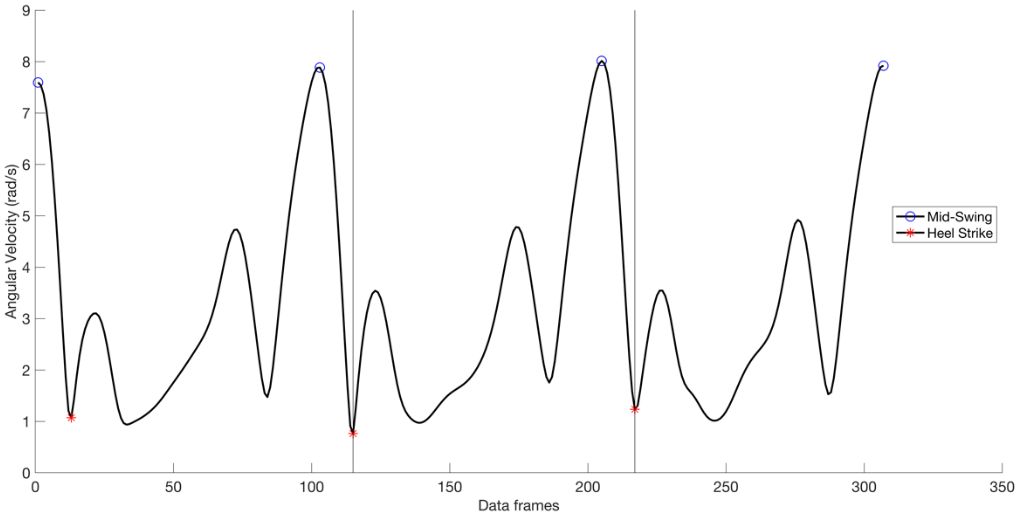
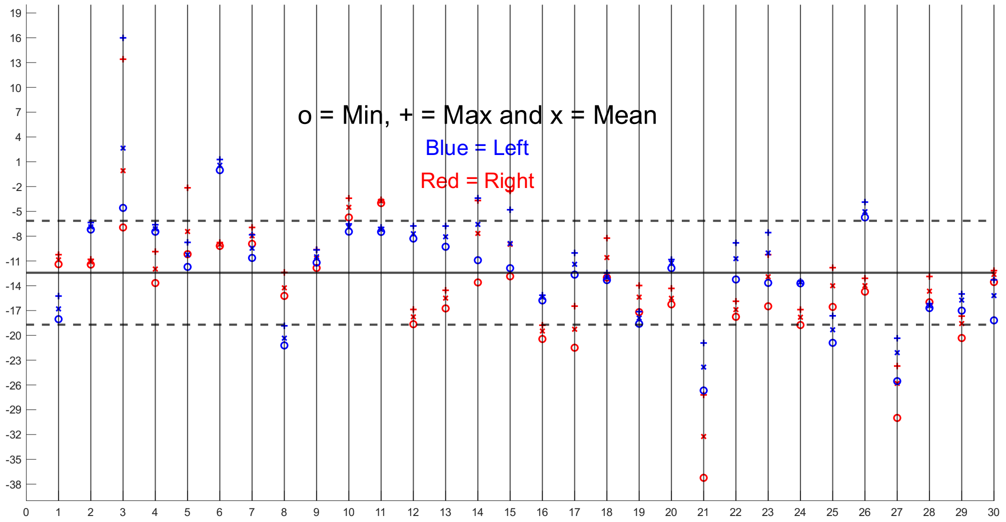


Figure 4. Knee-Hip Deviation Phase (DP) medians (interquartile range) on sloped, irregular, and banked surfaces during gait. Higher values indicate more variability. Bank-Lt: Banked-left; Bank-Rt: Banked right; Cobb: Cobblestone; Down: Slope-Down; Up: Slope-Up. Asterisk denotes Bonferroni-adjusted statistically significant finding ($p \leq 0.006$). Top and bottom row show results for stance and swing, respectively.

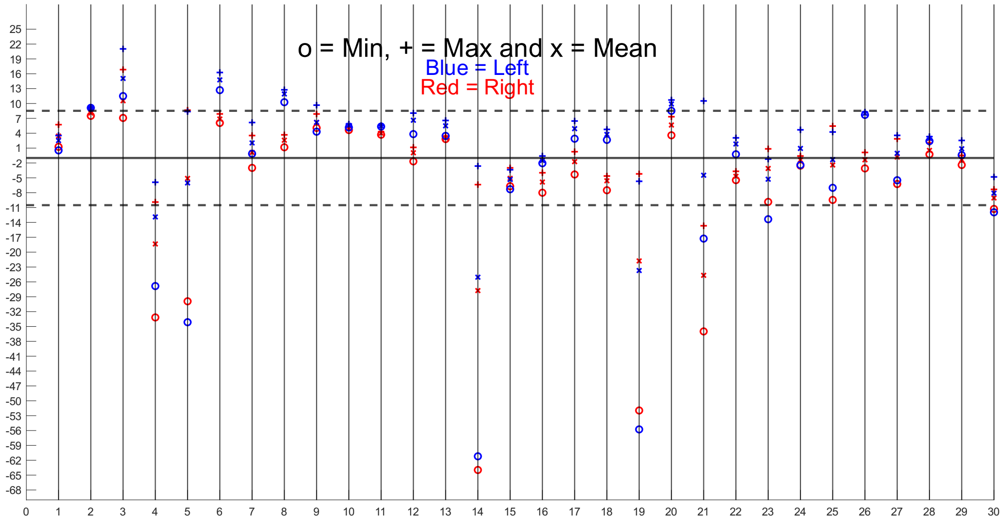
Supplemental material



Supplemental figure 1: Graphical representation of gait cycle detection using angular velocity of the inertial measurement unit at the shank segment based on [16]. The first minimum between two local maxima (blue circle) defines a heel-strike (red star). Vertical lines delineate typical gait cycle retained for analyses.



(a)



(b)

Supplemental Figure 2: Anatomical (static) offsets for raw (a) knee and (b) hip angles. Solid and dashed horizontal lines show mean and mean ± 1 standard deviation. Based on this analysis, knee joint flexion/extension values were adjusted by approximately -12 degrees. Hip angles were not adjusted.

Gait Event	**Flat**	**BnkL**	**BnkR**	**Cob**	**Grass**	**SlopeUp**	**SlopeDown**
MARP Stance	P	P	P	P	P	P	P
MARP Swing	P	P	P	P	P	P	P
DP Stance	NP	NP	NP	NP	NP	NP	NP
DP Swing	NP	NP	NP	NP	NP	NP	NP

Supplemental Table 1. Description of statistical test used to test main effect of outdoor surfaces on Knee-Hip Mean Absolute Relative Phase (MARP) and Deviation Phase (DP), where P denotes a parametric test (One-way repeated measure ANOVA) and NP denotes a non-parametric test (Friedman's ANOVA). BnkL: Banked left; BnkR: Banked right; Cob: Cobblestone;

Gait Event	**BnkL vs. BnkR**	**Flat vs. BnkR**	**Flat vs. BnkL**	**Cob vs. Grass**	**Flat vs. Cob**	**Flat vs. Grass**	**SlopeDown vs. SlopeUp**	**Flat vs. SlopeDown**	**Flat vs. SlopeUp**
MARP Stance	P	P	P	P	P	P	P	P	P
MARP Swing	P	P	P	P	P	P	P	P	P
DP Stance	NP	NP	NP	NP	NP	NP	NP	NP	NP
DP Swing	NP	NP	NP	NP	NP	NP	NP	NP	NP

Supplemental Table 2. Description of statistical test used for post-hoc comparisons of effects of outdoor surfaces on Knee-Hip Mean Absolute Relative Phase (MARP) and Deviation Phase (DP), where P denotes a parametric test (Paired t-test) and NP denotes a non-parametric test (Wilcoxon Signed-rank test). BnkL: Banked left; BnkR: Banked right; Cob: Cobblestone;