Journal of Biomechanics 206 (2026) 113504

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech

Differences in running kinematics and stride-to-stride variability between self-paced treadmill and overground running on two surfaces☆

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ARTICLE INFO

Keywords:
Inertial measurement units (IMUs)
Gait analysis
Locomotion
Sagittal-plane biomechanics
Running speed

ABSTRACT

Treadmills are widely used in running research, yet it remains unclear how closely self-paced treadmill running reflects overground running. To date, treadmill–overground comparisons have been limited to fixed-speed conditions. This study compared self-paced treadmill running with overground running on hard and soft surfaces. Twenty-one physically active young adults performed running trials under three conditions: self-paced treadmill, overground soft surface, and overground hard surface. Mean values and stride-to-stride variability were analyzed for kinematic variables, and time-continuous sagittal kinematics were assessed using statistical parametric mapping. Compared with both overground conditions, treadmill running showed small but systematic differences in mean kinematics, including higher cadence (< 2 strides/min; $p = 0.005$), lower duty factor (< 3 %; $p = 0.012$), shorter stance time (< 22 ms; $p = 0.002$), smaller shank angle at initial contact (< 3°; $p = 0.004$), and reduced sagittal hip and knee ROM during stance (< 4°; hip: $p < 0.001$; knee: $p = 0.001$). Time-continuous analysis showed reduced hip and knee flexion (up to ∼ 10°), and greater ankle dorsiflexion (up to ∼ 9°) across large portions of the stride. Stride-to-stride variability was lower on the treadmill, with significant effects for cadence ($p = 0.003$), stance time ($p = 0.019$), shank angle, and sagittal hip, knee, and ankle ROM (all $p < 0.001$). These findings suggest that self-paced treadmill running does not fully replicate overground running and that treadmill-derived results, particularly for variability analyses, should be interpreted with caution in relation to overground running.

1. Introduction

Running biomechanics research is frequently conducted on treadmills due to their practical and methodological advantages. Treadmills facilitate standardized running-speed conditions, continuous data collection over many strides, and allow integration with motion capture and force measurement systems in controlled laboratory environments. These features make treadmill running highly attractive for investigating kinematics, kinetics, and motor control. However, the extent to which treadmill findings generalize to overground running remains debated, particularly regarding movement variability and its temporal structure, as treadmill running has been associated with more regular stride-to-stride fluctuations than overground running (Lindsay et al., 2014). Although treadmill and overground running are largely comparable, small but systematic differences have been reported, particularly in sagittal-plane mechanics (Riley et al., 2008; Van Hooren et al., 2020). A systematic review and *meta*-analysis by Van Hooren et al. (2020) concluded that variables such as sagittal foot–ground angle at initial contact, knee flexion at initial contact, knee flexion range of motion (ROM) during stance, and vertical displacement of the pelvis differ between treadmill and overground running. Although sagittal trunk posture has received less specific attention in previous treadmill–overground comparisons, it remains highly relevant because trunk flexion can influence spatiotemporal variables and sagittal-plane lower limb kinematics (Carson et al., 2024; Warrener et al., 2021). Together, these findings suggest that treadmill running reproduces many characteristics of overground running, but is not fully equivalent.

The mechanisms underlying these treadmill–overground differences are not fully clear, but one potential factor is the way speed is controlled during treadmill running. In conventional fixed-speed treadmill running, runners must match an externally imposed average belt speed, whereas overground running allows step-to-step speed adjustments. This imposed speed regulation may constrain how runners adjust successive strides, even when average treadmill speed is matched to

☆ This article is part of a special issue entitled: 'Biomechanics in AI Age' published in Journal of Biomechanics.

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https://doi.org/10.1016/j.jbiomech.2026.113504
Accepted 30 July 2026
Available online 31 July 2026

overground speed (Darendeli et al., 2023; Lindsay et al., 2014). In particular, stride timing appears to vary in a more constrained way during treadmill than overground running, especially at non-preferred speeds, suggesting altered temporal organization of stride-to-stride variability (Lindsay et al., 2014). Similar observations have been reported in walking, where treadmill gait is associated with altered temporal organization and decreased variability of spatiotemporal variables (Dingwell et al., 2001; Terrier and Dériaz, 2011; Warabi et al., 2005).

Self-paced treadmill systems may help address this limitation by allowing users to regulate belt speed dynamically (Sloot et al., 2014; Theunissen et al., 2022). Evidence from walking studies suggests that self-paced treadmill modes can increase gait variability compared with fixed-speed treadmill walking, thereby more closely resembling overground walking (Wiens et al., 2019). However, self-paced treadmill running has not yet been directly compared with overground conditions. To date, it is unclear to what extent self-paced treadmill running reflects overground running, particularly in terms of stride-to-stride kinematic variability.

Another factor that may contribute to treadmill–overground differences is surface mechanical behavior. Treadmill surfaces differ from many overground running surfaces in compliance and damping (Colino et al., 2020), and runners adapt leg-spring behavior accordingly (Ferris et al., 1998; Kerdok et al., 2002). Therefore, some treadmill–overground differences may reflect not only speed-control constraints, but also adaptations to differences in surface behavior (Van Hooren et al., 2020). Including overground conditions with different surface properties may therefore help clarify whether observed differences are primarily treadmill-specific or also related to the overground surface condition.

The present study aimed to address these research gaps by comparing mean kinematics and stride-to-stride variability between self-paced treadmill and overground running on two surfaces (hard and soft). Specifically, mean values and stride-to-stride variability of spatiotemporal variables, lower limb joint kinematics, and trunk posture were analyzed. It was hypothesized that (1) self-paced treadmill running would show small but systematic differences from overground running in mean kinematic variables, regardless of overground surface type (Riley et al., 2008; Van Hooren et al., 2020); and (2) stride-to-stride variability would be lower during self-paced treadmill running than during overground running on both surfaces, reflecting persistent treadmill-related constraints despite dynamic speed regulation.

2. Methods

2.1. Participants

An *a priori* power analysis was conducted for a repeated-measures ANOVA (rmANOVA) comparing three experimental conditions, based on previously reported medium effect sizes (Moon et al., 2025). Assuming an expected effect size of $f = 0.29$, a desired statistical power of 0.80, and an alpha level of 0.05, the required sample size was calculated to be $n = 21$ using G*Power (Version 3.1.9.7). To account for a potential dropout rate, the sample size was increased by 10 %, resulting in the recruitment of 23 participants. During data processing, two participants were excluded (one due to poor data quality and one due to non-matching running speeds between conditions). The final sample consisted of 21 participants (9 female; age: 26.05 ± 3.64 years; height: 1.72 ± 0.09 m; body mass: 68.71 ± 9.35 kg). All participants were physically active, regularly engaged in running, and reported no current musculoskeletal injuries. The study protocol was approved by the ethics committee of the Karlsruhe Institute of Technology (Application number: A2025-128), and all participants provided informed consent prior to participation.

2.2. Study design

Participants attended a single experimental session and performed running trials under three conditions in a counterbalanced order: treadmill running (TRDM), overground running on a soft surface (OVRS), and overground running on a hard surface (OVRH). The individual order of experimental conditions is provided in Supplementary Table S1. All participants wore the same running shoe model, with shoe size selected individually according to each participant's foot size (EU sizes 37–46). The session began with a standardized warm-up consisting of 6 min of walking followed by 4 min of running at a self-selected comfortable speed (Lavcanska et al., 2005). For the TRDM condition, both the warm-up and running trials were performed at a 0° slope on an instrumented treadmill (M-Gait, Motek Medical, Amsterdam, The Netherlands) with a 2 × 1 m running surface, two integrated force plates, a maximum forward belt speed of 25 km/h, a speed resolution of 0.01 km/h, and a maximum acceleration of 15 m/s^2. For the overground conditions, the warm-up was performed in the sports hall. If TRDM was not the first condition, participants additionally completed 2–3 min of familiarization with treadmill running in self-paced mode before the TRDM trials. Each condition (TRDM, OVRS, and OVRH) consisted of two 1-minute trials. Participants established their self-selected speed in the first condition, and this speed was subsequently used to match running speed across the remaining conditions. Before each transition between treadmill and overground running, participants completed a 1–2 min familiarization period during which running speed was checked and verbal feedback was provided until the target speed was reached. During the trials, speed-related verbal feedback was also provided identically across all three conditions when participants ran slightly faster or slower than the target speed. TRDM was performed in a self-paced mode, with belt speed continuously adjusted via a feedback-control algorithm based on the anterior–posterior position of the pelvis (Motek Medical, 2023). Participants wore an overhead safety harness during treadmill trials, which was adjusted to avoid continuous tension during running and served only as fall protection in case of balance loss. Overground trials were conducted on a 40 m indoor runway under two surface conditions. OVRS was performed on a compliant foam-based gymnastics mat placed on the sports hall floor, whereas OVRH was performed directly on the standard rigid synthetic sports hall floor. Participants ran continuously along the 40 m runway and turned around at each end to continue in the opposite direction, covering a total distance of 240 m per trial.

2.3. Data acquisition and preprocessing

Three-dimensional whole-body kinematics were recorded using an inertial measurement unit (IMU) system (3D Ultium Motion, Noraxon, USA) at 200 Hz (accelerometers: ±200 g; gyroscopes: ±7000°/s). Sixteen IMUs were attached to the feet, shanks, thighs, pelvis, lower and upper spine, upper arms, forearms, hands, and head according to manufacturer guidelines. For each condition, a walking calibration was performed to minimize possible drift or sensor displacement after transitions between treadmill and overground running locations. Static upright-standing calibration trials were additionally recorded before and after each trial. Although the repeated calibration procedure was intended to improve data quality across conditions, small calibration-to-calibration variability cannot be fully excluded. Ground reaction forces were collected at 1000 Hz from force plates embedded in the treadmill during TRDM trials.

2.4. Data analysis

Kinematic data were obtained from the Noraxon myoMOTION (Version MR 4.0.4) full-body model after system calibration using the walking calibration routine. Sagittal trunk, hip, knee, and ankle angles were exported from myoMOTION model output for further analysis in MATLAB (R2024a; MathWorks Inc., Natick, MA, USA). The exported joint-angle data were processed using the default *Model Optimizer* in the Noraxon software. No additional filtering was applied after export. Positive values indicated forward trunk lean, hip flexion, knee flexion, and ankle dorsiflexion.

Running speed was used to verify speed matching between conditions. During TRDM, mean speed was obtained from treadmill belt-speed output in D-Flow (Motek Medical, Amsterdam, The Netherlands). For OVRS and OVRH, running speed was determined from stopwatch timing of consecutive 20 m straight sections of the runway, and section speeds were averaged per trial.

Initial contact was identified as zero-crossings in shank angular velocity (Fadillioglu et al., 2020; Kiernan et al., 2023). Toe-off was identified at the moment of maximum knee extension in late stance (Fellin et al., 2010; King et al., 2019). In TRDM, gait events detected from force data using a 20-N threshold were used as the reference for validating IMU-based gait-event detection, whereas stride segmentation in all conditions was based on IMU-based events. This comparison was intended as a setup-specific quality check rather than as a formal validation of the event-detection method. Agreement was assessed from matched events, with signed differences calculated as IMU-based minus force-based event timing. Mean absolute differences were 15 ms for initial contact and 20 ms for toe-off. Signed differences were − 10.9 ± 21.0 ms for initial contact and + 4.0 ± 26.9 ms for toe-off, corresponding to − 4.0 ± 7.8 % and + 1.5 ± 10.0 % of mean force-based stance time, respectively. Thus, the IMU-based method detected initial contact slightly earlier and toe-off slightly later, resulting in a modest overestimation of stance duration by 14.8 ± 31.3 ms.

For each condition and side, 80 valid strides were included in the analysis, consisting of 40 strides selected from the middle portion of each of the two trials. Strides from the beginning and end of each trial were excluded. Thus, 80 right and 80 left strides were analyzed per condition. In the overground conditions, the first five strides after each turn were additionally excluded to minimize the influence of turning. Kinematic variables were calculated on a stride-by-stride basis, including cadence, duty factor, stance time, shank angle at initial contact, and sagittal hip, knee, and ankle ROM during stance (Van Hooren et al., 2020; van Oeveren et al., 2021). Sagittal trunk angle (forward/backward tilt relative to the ground), as well as hip, knee, and ankle joint kinematics, were additionally time-normalized to 101 points per stride. For each participant, condition and side, mean values and coefficients of variation (CoV) were computed across 80 strides. Variables were then averaged across left and right sides for the main analysis because separate left- and right-side analyses showed the same pattern of significant condition effects for all analyzed variables.

2.5. Statistics

Statistical analyses of discrete variables were performed using IBM SPSS Statistics (Version 29.0; IBM Corp., Armonk, NY, USA). The analyzed variables were mean running speed and the mean and CoV of cadence, duty factor, stance time, shank angle at initial contact, and sagittal hip, knee, and ankle ROM during stance. Normality was assessed using the Shapiro–Wilk test. Differences between conditions (TRDM, OVRS, and OVRH) were evaluated using one-way repeated-measures ANOVA (rmANOVA). Significant main effects were followed by post-hoc paired *t*-tests with Holm–Bonferroni correction. Effect sizes for the ANOVA were expressed as partial eta squared (η_p^2) and interpreted as small ($\leq$ 0.06), medium (0.06–0.14), or large ($\geq$ 0.14). Effect sizes for post-hoc comparisons were calculated using Cohen's *d* and interpreted as small ($\leq$ 0.50), medium (0.50–0.80), or large ($\geq$ 0.80) (Cohen, 1988). Statistical significance was set at $\alpha = 0.05$.

Time-continuous differences across the running stride were assessed using statistical parametric mapping (SPM) one-way rmANOVA implemented using the spm1d toolbox in MATLAB (Pataky et al., 2019). For *post-hoc* analysis, paired *t*-tests were conducted with Bonferroni correction. Normality of residuals was evaluated using SPM normality tests; when violated, non-parametric permutation tests (1000 iterations) were applied. Statistical significance was set at $\alpha = 0.05$, and significant clusters across the stride were identified with corresponding p-values reported.

3. Results

Mean running speed did not differ between conditions (TRDM: 2.61 ± 0.43 m/s; OVRS: 2.60 ± 0.41 m/s; OVRH: 2.64 ± 0.40 m/s) (Table 1). Individual running speeds for each participant and condition are provided in Supplementary Table S1.

3.1. Mean kinematic differences between conditions

Cadence ($p = 0.005$), duty factor ($p = 0.012$), and stance time ($p = 0.002$) differed between conditions (Table 1). Cadence was higher in TRDM compared to OVRS ($p = 0.004$) and OVRH ($p = 0.031$), and higher in OVRH compared to OVRS ($p = 0.044$). Duty factor was lower in TRDM compared to OVRS ($p = 0.015$) and OVRH ($p = 0.008$), and lower in OVRS compared to OVRH ($p < 0.001$). Stance time was shorter in TRDM compared to OVRS ($p = 0.004$) and OVRH ($p = 0.003$) (Table 2).

Shank angle at initial contact ($p = 0.004$), sagittal hip ROM ($p < 0.001$), sagittal knee ROM ($p = 0.001$), and sagittal ankle ROM ($p = 0.021$) likewise differed between conditions (Table 1). Shank angle at initial contact was lower in TRDM than in OVRS ($p < 0.001$) and OVRH ($p = 0.030$). Sagittal hip ROM during stance was greater in OVRS ($p = 0.001$) and OVRH ($p = 0.002$) than in TRDM. Sagittal knee ROM during stance was greater in OVRS ($p = 0.012$) and OVRH ($p = 0.001$) than in

Table 1
Repeated-measures ANOVA results for mean values and coefficients of variation of kinematic variables across running conditions. Results are shown for treadmill running (TRDM), overground running on soft surface (OVRS), and overground running on hard surface (OVRH), together with F-values, p-values, and effect sizes (η_p^2). IC: initial contact, ROM: range of motion.

Mean	TRDM	OVRS	OVRH	F	p	η_p^2
Speed (m/s)	2.61 ± 0.43	2.60 ± 0.41	2.64 ± 0.40	1.175	0.319	0.06
Cadence (strides/min)	80.44 ± 3.62	78.87 ± 3.99	79.30 ± 3.66	7.741	0.005	0.28
Duty factor (%)	37.00 ± 4.16	38.72 ± 2.53	39.32 ± 2.61	7.355	0.012	0.27
Stance time (s)	0.28 ± 0.03	0.30 ± 0.03	0.30 ± 0.03	11.154	0.002	0.36
Shank angle at IC (°)	13.15 ± 6.53	15.36 ± 6.11	14.82 ± 5.87	6.261	0.004	0.24
Sagittal hip ROM (°)	36.50 ± 4.00	39.60 ± 5.55	39.73 ± 5.32	11.634	<0.001	0.37
Sagittal knee ROM (°)	30.19 ± 4.95	31.73 ± 4.61	32.48 ± 4.66	10.478	0.001	0.34
Sagittal ankle ROM (°)	32.28 ± 5.19	32.96 ± 7.24	35.52 ± 7.77	5.538	0.021	0.22
Coefficient of variation	TRDM	OVRS	OVRH	F	p	η_p^2
Cadence (%)	1.42 ± 0.38	1.73 ± 0.56	1.71 ± 0.69	6.689	0.003	0.25
Duty factor (%)	2.81 ± 1.54	2.99 ± 0.72	3.06 ± 0.78	0.422	0.549	0.02
Stance time (%)	3.05 ± 1.45	3.81 ± 1.04	3.86 ± 0.95	5.580	0.019	0.22
Shank angle at IC (%)	16.45 ± 9.73	38.20 ± 19.08	37.54 ± 12.80	22.234	<0.001	0.55
Sagittal hip ROM (%)	5.11 ± 1.19	12.00 ± 3.80	11.54 ± 4.88	27.795	<0.001	0.58
Sagittal knee ROM (%)	6.37 ± 2.14	11.27 ± 3.09	11.15 ± 3.13	52.855	<0.001	0.73
Sagittal ankle ROM (%)	6.38 ± 2.26	11.25 ± 2.20	11.26 ± 3.33	70.794	<0.001	0.78

Table 2
Post-hoc paired t-test comparisons for mean values and coefficients of variation of kinematic variables between running conditions. Pairwise comparisons are presented for treadmill running (TRDM), overground running on soft surface (OVRS), and overground running on hard surface (OVRH), including p-values, effect sizes (Cohen's $|d|$), and the condition with the higher value. IC: initial contact, ROM: range of motion.

Mean	TRDM vs OVRS			TRDM vs OVRH			OVRS vs OVRH		
	p	$|d|$	higher	p	$|d|$	higher	p	$|d|$	higher
Cadence (strides/min)	0.004	0.75	TRDM	0.031	0.51	TRDM	0.044	0.39	OVRH
Duty factor (%)	0.015	0.51	OVRS	0.008	0.65	OVRH	<0.001	0.84	OVRH
Stance time (s)	0.004	0.71	OVRS	0.003	0.77	OVRH	0.077	0.32	–
Shank angle at IC (°)	<0.001	0.87	OVRS	0.030	0.51	OVRH	0.214	0.18	–
Sagittal hip ROM (°)	0.001	0.82	OVRS	0.002	0.78	OVRH	0.389	0.06	–
Sagittal knee ROM (°)	0.012	0.60	OVRS	0.001	0.82	OVRH	0.012	0.53	OVRH
Sagittal ankle ROM (°)	0.275	0.13	–	0.011	0.55	OVRH	<0.001	1.09	OVRH

Coefficient of variation	TRDM vs OVRS			TRDM vs OVRH			OVRS vs OVRH		
	p	$|d|$	higher	p	$|d|$	higher	p	$|d|$	higher
Cadence (%)	0.003	0.76	OVRS	0.022	0.54	OVRH	0.370	0.07	–
Stance time (%)	0.024	0.57	OVRS	0.026	0.52	OVRH	0.361	0.08	–
Shank angle at IC (%)	<0.001	1.24	OVRS	<0.001	1.49	OVRH	0.446	0.03	–
Sagittal hip ROM (%)	<0.001	1.64	OVRS	<0.001	1.25	OVRH	0.325	0.10	–
Sagittal knee ROM (%)	<0.001	1.54	OVRS	<0.001	1.13	OVRH	0.414	0.04	–
Sagittal ankle ROM (%)	<0.001	2.33	OVRS	<0.001	1.88	OVRH	0.491	0.01	–

TRDM, and greater in OVRH than in OVRS ($p = 0.012$). Sagittal ankle ROM during stance was greater in OVRH than in TRDM ($p = 0.011$) and OVRS ($p < 0.001$) (Table 2).

SPM analysis revealed significant differences between conditions across the stride for all sagittal-plane variables (Fig. 1). Compared with both overground conditions, TRDM showed greater ankle dorsiflexion, and reduced hip and knee flexion across large portions of the stride (Fig. 2). Additional differences between OVRS and OVRH were observed primarily during swing, with OVRS showing greater hip and knee flexion. No significant pairwise differences were observed for sagittal trunk angle.

3.2. Stride-to-stride variability differences between conditions

For spatiotemporal variability, the CoV of cadence ($p = 0.003$) and stance time ($p = 0.019$) differed between conditions (Table 1). Variability was lower in TRDM than in OVRS (cadence: $p = 0.003$; stance time: $p = 0.024$) and OVRH (cadence: $p = 0.022$; stance time: $p = 0.026$) (Table 2).

For kinematic variability, shank angle at initial contact ($p < 0.001$), sagittal hip ROM ($p < 0.001$), sagittal knee ROM ($p < 0.001$), and sagittal ankle ROM ($p < 0.001$) differed between conditions (Table 1). For all variables, TRDM showed lower variability than both OVRS and OVRH (all $p < 0.001$) (Table 2).

4. Discussion

The present study aimed to compare running kinematics and stride-to-stride variability during self-paced treadmill and overground running on two different surfaces. Despite matched running speed, self-paced treadmill running showed small but systematic differences from overground running, including higher cadence, lower duty factor, shorter stance time, smaller shank angle at initial contact, and reduced sagittal hip and knee ROM during stance. The SPM analysis showed reduced hip and knee flexion and greater dorsiflexion across large parts of the stride compared with overground running. Moreover, stride-to-stride variability was consistently lower on the treadmill across most kinematic variables. Taken together, these results suggest that self-paced treadmill running does not fully reproduce overground running mechanics, with differences consistently observed relative to overground running on both soft and hard surfaces.

4.1. Self-paced treadmill running induces small but systematic changes in mean kinematic variables

The first hypothesis was supported, as self-paced treadmill running showed small but systematic differences from overground running across both overground surfaces in mean kinematic variables. Specifically, compared with overground running, self-paced treadmill running was characterized by modest differences in the discrete variables, including higher cadence (< 2 strides/min), lower duty factor (< 3 %), shorter stance time (< 22 ms), smaller shank angle at initial contact (< 3°), and reduced lower-limb ROM during stance (< 4°). These effects were systematic and consistently observed across both overground conditions, making it unlikely that they were solely due to random measurement noise. However, the extent to which the smaller differences exceeded the measurement error of the IMU-based system cannot be determined from the present data alone.

The SPM analysis revealed larger time-continuous differences between treadmill and overground running, with ankle dorsiflexion differing by up to 9° and hip and knee flexion by up to 10°. In contrast, differences between the soft and hard overground conditions were localized and less consistent, indicating that treadmill did not represent an intermediate condition between soft and hard overground running, but rather showed a distinct treadmill-specific kinematic pattern.

Together, these findings indicate that self-paced treadmill running is broadly comparable to overground running, but does not fully eliminate treadmill-related adaptations. This interpretation is consistent with previous work showing that treadmill and overground running are broadly comparable in mean kinematic variables, although the available evidence is based on quasi-constant-speed motorized treadmill running rather than self-paced treadmill running (Van Hooren et al., 2020). In the present study, the belt-speed output showed clear time-varying adjustments, indicating that the self-paced condition did not simply resemble a near-constant-speed treadmill condition. The combination of higher cadence, lower duty factor, shorter stance time, reduced hip and knee flexion together with smaller ROM during stance suggests a treadmill-specific and constrained running pattern. A plausible explanation is that, even in self-paced mode, treadmill running remains influenced by the requirement to maintain a consistent position near the center of the treadmill and by the characteristics of the self-pacing algorithm.

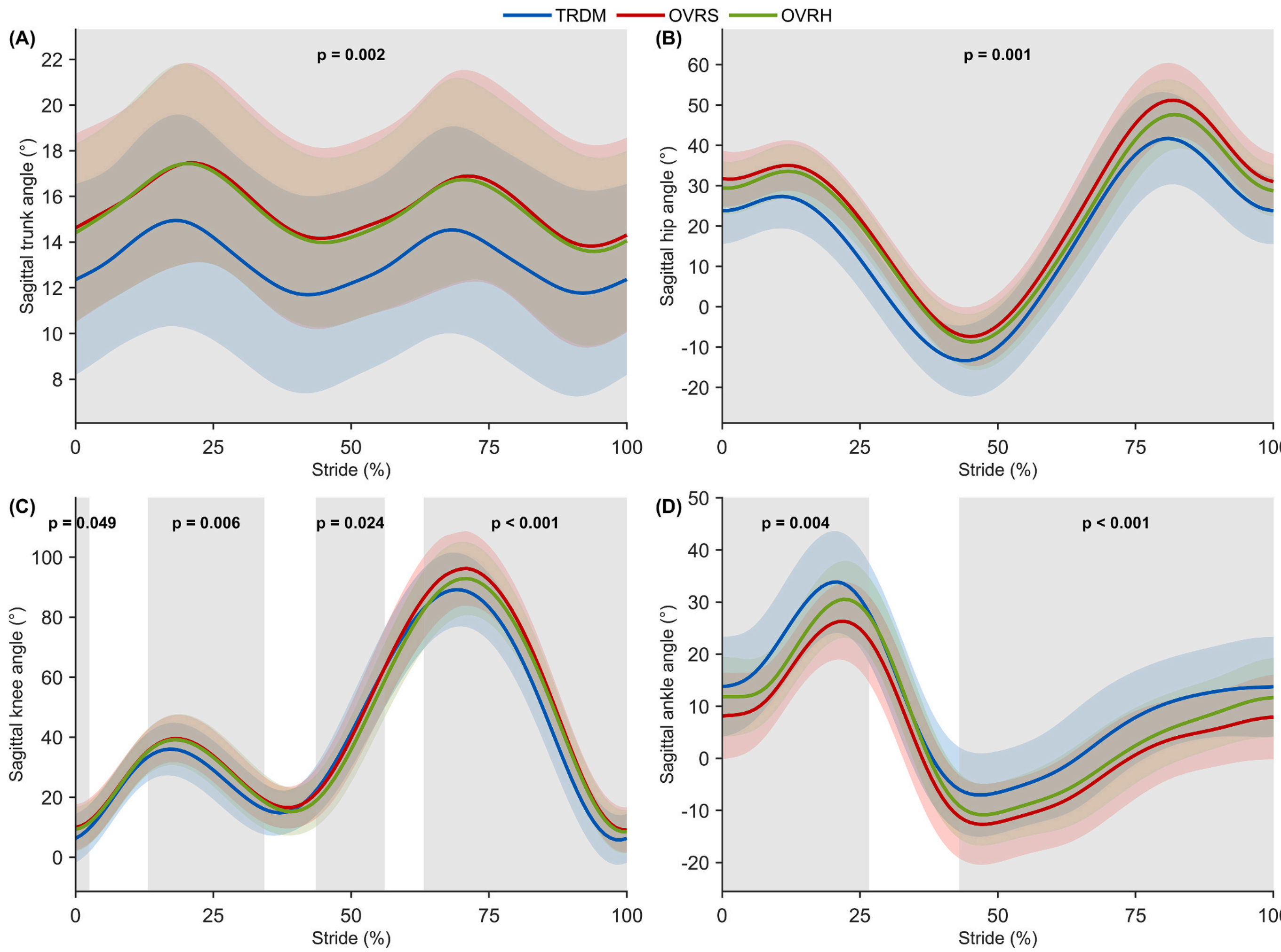

Fig. 1. Sagittal trunk (A), hip (B), knee (C), and ankle angles (D) across the stride during treadmill running (TRDM, blue), overground running on a soft surface (OVRS, red), and overground running on a hard surface (OVRH, green). Positive values indicate forward trunk lean, hip flexion, knee flexion, and ankle dorsiflexion. Solid lines represent condition means, and shaded colored bands indicate inter-subject variability (± SD). Grey shaded regions denote significant clusters identified using Statistical Parametric Mapping, indicating differences between running conditions across the stride. Corresponding cluster-level p-values are displayed above each shaded region.

4.2. Self-paced treadmill running leads to less stride-to-stride variability

The second hypothesis was supported, as stride-to-stride variability was lower during self-paced treadmill running than during overground running on both surfaces for most kinematic variables, with duty factor being the only exception. Specifically, variability in cadence, stance time, shank angle at initial contact, and sagittal hip, knee, and ankle ROM was reduced on the treadmill. These findings suggest that allowing dynamic speed regulation is not sufficient to restore the level of stride-to-stride fluctuation observed during overground running. The lower variability observed here reflects the magnitude of stride-to-stride fluctuations and should be distinguished from previous literature that examined the structure of variability during fixed-speed running. For example, Lindsay et al. (2014) reported that fixed-speed treadmill running showed a more regular temporal structure of stride timing than overground running, which they interpreted as reflecting more constrained stride-to-stride regulation. The present findings extend this evidence by showing that, even during self-paced treadmill running, the magnitude of kinematic variability remained lower than during overground running.

A possible explanation is that, although self-paced control removes the externally imposed fixed belt speed, treadmill running still requires continuous positional regulation relative to the treadmill center (Castano and Huang, 2021; Song et al., 2020). The need to remain near the treadmill center may limit the available movement solutions and thereby attenuate natural stride-to-stride fluctuations characteristic of overground locomotion (Dingwell et al., 2001; Rohafza et al., 2022). The present findings show that variability remained lower on the treadmill than during overground running on both surfaces, despite the added freedom of self-paced speed control.

5. Limitations

Several limitations should be considered when interpreting the present findings. First, running was performed at a comfortable speed (~9.4 km/h on average) in physically active young adults with regular running experience. Therefore, the findings may not generalize to other running speeds or populations with different levels of running expertise, as kinematic variables can vary with speed and participant characteristics (Novacheck, 1998; Shen et al., 2026). Second, although running speed was matched between conditions, overground speed was estimated from section times rather than continuous measurement, which may have reduced sensitivity to subtle stride-to-stride speed fluctuations. Third, overground running was performed on a 40 m indoor runway with repeated turns, which may have influenced running movement and variability compared with continuous straight-line

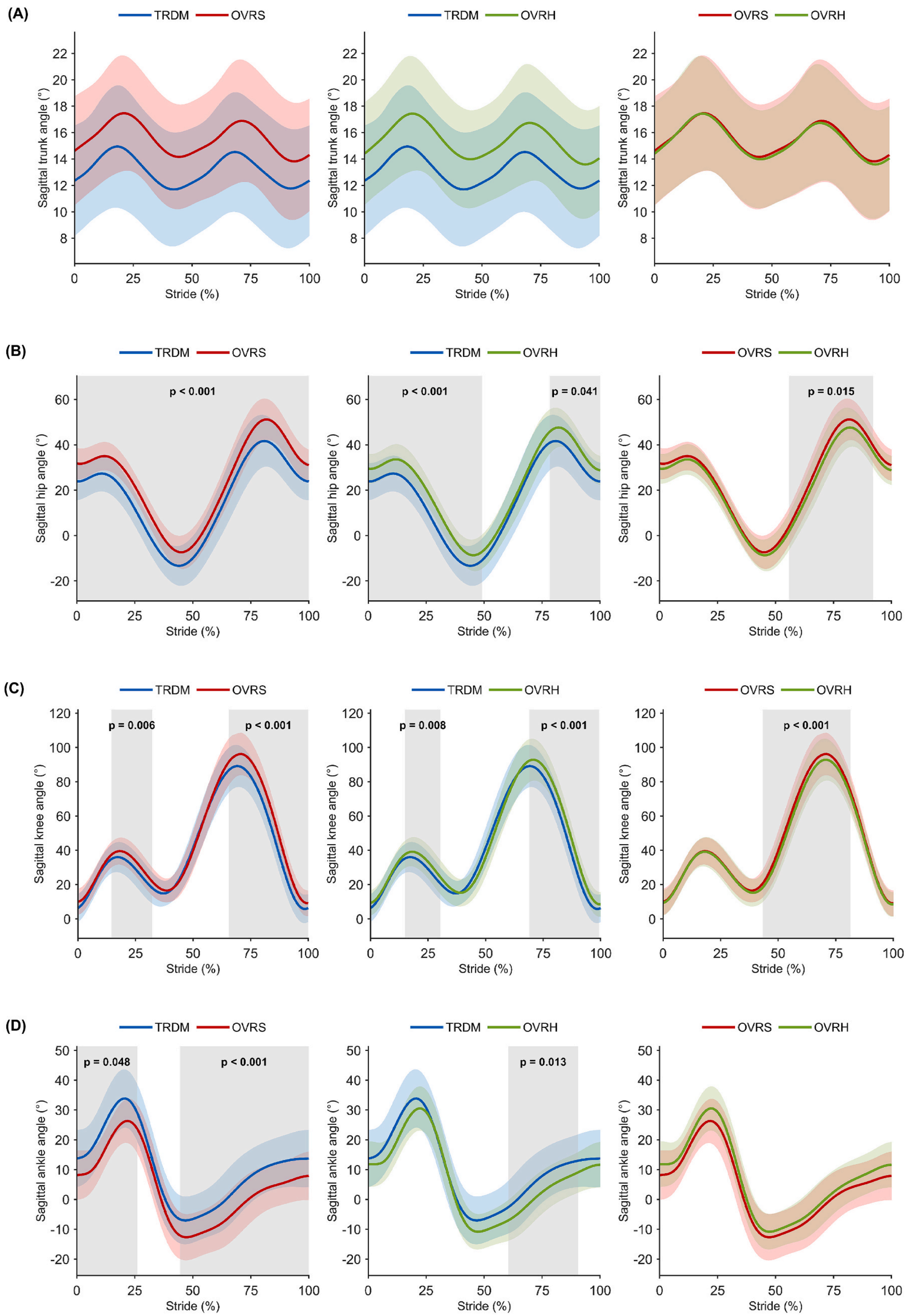

Fig. 2. Pairwise comparisons of sagittal trunk (A), hip (B), knee (C), and ankle angles (D) across the stride between treadmill running (TRDM, blue), overground running on a soft surface (OVRS, red), and overground running on a hard surface (OVRH, green). Positive values indicate forward trunk lean, hip flexion, knee flexion, and ankle dorsiflexion. Colored lines represent condition-specific mean profiles, and shaded colored bands indicate inter-subject variability (± standard deviation). Grey shaded regions indicate significant clusters identified using Statistical Parametric Mapping, with corresponding cluster-level p-values displayed above each shaded region.

running. However, to minimize the possible effects of turning, the first five strides after each turn were excluded from the analysis. Fourth, the IMU-based kinematic and event-detection data were not validated against a reference system for the full protocol. The treadmill-based validation indicated a modest overestimation of stance duration by the IMU-based event detection (14.8 ± 31.3 ms), but a comparable force-based reference was not available for the overground conditions. Although errors in event-dependent variables cannot be excluded, the same IMU-based event-detection algorithm was applied in all conditions. Therefore, systematic timing errors likely affected all conditions similarly and should have less influence on between-condition comparisons. In addition, previous validation studies using different IMU systems, movement tasks, speeds, and processing pipelines have reported good-to-excellent sagittal-plane waveform agreement, but also joint-angle errors that can be comparable to some of the smaller differences observed in the present study (Bessone et al., 2022; Heuvelmans et al., 2025; Nijmeijer et al., 2023; Nüesch et al., 2017). Therefore, particularly the smaller angular differences observed here should be interpreted cautiously, although their consistency across both overground comparisons and 80 strides per side suggests a systematic pattern rather than random. Fifth, the mechanical properties of the treadmill and overground surfaces were not quantified; therefore, surface-related interpretations are based on the intended soft–hard contrast rather than measured stiffness or damping. Sixth, the findings are specific to the treadmill system and self-paced control algorithm used in this study and may not generalize directly to other self-paced treadmill setups (Castano and Huang, 2021). Finally, the present study focused on the magnitude of stride-to-stride variability and did not examine its temporal or coordinative structure. Future studies could therefore complement these findings by applying methods that address the structure of variability, such as nonlinear measures (Stergiou and Decker, 2011) or coordination-based approaches (Kettner et al., 2025; Möhler et al., 2019).

6. Conclusion

Self-paced treadmill running was broadly comparable to overground running at matched speeds, but not fully representative of it. Compared with both overground conditions, treadmill running was characterized by higher cadence, lower duty factor, shorter stance time, less hip and knee flexion, and reduced hip and knee excursions during stance. Furthermore, stride-to-stride variability was consistently lower across most kinematic variables. Because these differences were evident relative to both overground surfaces, they likely reflect constraints inherent to treadmill running rather than effects of surface type alone. To the best of our knowledge, this is the first study to directly compare self-paced treadmill and overground running on two different overground surfaces. From a practical perspective, self-paced treadmills may be useful in clinical, rehabilitation, and research settings because they allow controlled assessment over many consecutive strides with dynamic speed regulation. However, treadmill-derived outcomes should not be assumed to fully represent overground running, particularly with respect to the mean values and stride-to-stride variability of kinematic variables.

CRediT authorship contribution statement

Cagla Kettner: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vincent Alexander Zengerle:** Writing – review & editing, Data curation, Conceptualization. **Thorsten Stein:** Writing – review & editing, Supervision, Funding acquisition.

Funding

The treadmill used in this study was funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG; grant number 531599700). Open Access funding was enabled and organized by Projekt DEAL.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors acknowledge support from the KIT Publication Fund of the Karlsruhe Institute of Technology and the use of OpenAI's ChatGPT (version 5.3) for language editing and readability improvement.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2026.113504.

Data availability

Data will be made available on request.

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