



Speed-dependent stance time adaptations in long-distance runners with and without a history of knee injury

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ABSTRACT

Running-related knee injuries are common in long-distance runners and may lead to persistent biomechanical adaptations even after return to sport. This study aimed to compare spatiotemporal parameters of the running gait cycle between long-distance runners with and without a history of knee injury during incremental treadmill running. Thirty male long-distance recreational runners (15 with previous knee injury and 15 controls) were assessed using three-dimensional motion capture at 9, 11, and 13 km/h. Temporal variables included stride time, stance time, swing time, phase distribution, and cadence. Mixed-model repeated measures analyses and Mann–Whitney U tests were applied ($p < .05$). No significant main effects or interactions were observed, indicating a preserved global temporal organization across speeds. However, runners with a history of injury demonstrated greater stance time at 9 km/h (right limb) and 11 km/h (left limb). These findings suggest the presence of subtle, speed-dependent adaptations in temporal running mechanics, particularly during the stance phase. Such localized adjustments may be relevant for understanding injury recurrence and guiding biomechanical assessment in running populations.

Keywords: Biomechanics, Spatiotemporal parameters, Treadmill running, Gait mechanics, Overuse injury.

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INTRODUCTION

Running-related injuries represent a major concern in long-distance runners due to the repetitive mechanical demands imposed on the musculoskeletal system. Among these injuries, the knee is one of the most frequently affected anatomical regions, largely as a consequence of cumulative loading during running activities. Injury incidence has been reported between 2.5 and 33 cases per 1,000 hours of running, reflecting the substantial mechanical stress associated with training and competition (Bertelsen et al., 2017; Videbaek et al., 2015). Furthermore, a history of injury has consistently been identified as one of the strongest predictors of future injury, suggesting that residual biomechanical alterations may persist even after athletes return to sport (Van Poppel et al., 2021).

From a biomechanical standpoint, running is a cyclic locomotor task characterized by alternating stance and swing phases, where movement is organized through coordinated temporal and spatial patterns. The analysis of spatiotemporal parameters provides valuable insight into the structure of the gait cycle and the distribution of mechanical demands across the lower extremities (Kapri et al., 2021; Van Oeveren et al., 2024). Variables such as stride time, stance time, swing time, and cadence are commonly used to describe running mechanics and have been associated with performance, efficiency, and injury risk.

Among these variables, stance time is of particular interest, as it represents the period during which the foot remains in contact with the ground, and external forces are transmitted through the lower limb. Changes in stance duration may influence the temporal distribution of mechanical demands and reflect adjustments in motor control strategies during running. Previous studies have shown that alterations in the stance phase are associated with modifications in joint kinematics, impact attenuation, and neuromuscular coordination, particularly in populations with musculoskeletal impairments (Esculier et al., 2015; Neal et al., 2019; Yang et al., 2022).

Despite the growing body of literature on running biomechanics, most studies examining knee-related conditions have focused on symptomatic individuals or clinical populations. In contrast, less attention has been given to runners who have returned to sport and are currently asymptomatic but present a history of injury. This distinction is particularly relevant, as these individuals may exhibit subtle biomechanical adaptations that are not readily observable through global measures but could still influence injury recurrence risk.

In addition to injury history, running mechanics are influenced by external demands such as speed. Incremental treadmill protocols have been widely used to evaluate how biomechanical variables respond to increasing running intensity under controlled conditions. Evidence suggests that higher running speeds are associated with reductions in stance time, increases in cadence, and changes in stride characteristics, reflecting the adaptive behaviour of the locomotor system in response to greater mechanical demands (van Oeveren et al., 2024; Wang et al., 2025). However, it remains unclear whether these speed-dependent adaptations are consistent across individuals with different injury backgrounds.

Understanding how runners with and without a history of knee injury respond to increasing running speeds may provide relevant insights into the persistence of biomechanical adaptations following injury. In particular, examining temporal parameters may help identify subtle differences in movement organization that are not evident through global performance measures. These differences could reflect compensatory strategies or residual adaptations that influence how mechanical demands are managed during running.

Therefore, the aim of this study was to compare spatiotemporal parameters of the running gait cycle, with a specific focus on stance time, between long-distance runners with and without a history of knee injury during an incremental treadmill protocol. It was hypothesized that runners with previous injury would exhibit speed-dependent differences in temporal parameters, particularly in stance time, reflecting subtle adaptations in running mechanics.

MATERIAL AND METHODS

Participants

Thirty male recreational long-distance runners ($n = 30$) participated in this study. Participants were divided into two groups: runners with a history of knee injury ($n = 15$) and runners without a history of injury ($n = 15$). A history of injury was defined as a previously clinically diagnosed knee injury, with no current pain or functional limitations at the time of testing. All participants were actively training and were able to complete the protocol without interruption. Participants completed a questionnaire on their injury history and the Spanish version of the Knee Injury and Osteoarthritis Outcome Score –KOOS– (Vaquero et al., 2014). Participants were classified with and without a history of knee injury based on the information provided in the injury history questionnaire and the KOOS results, to identify both the presence of previous injuries and the current functional status of the knee joint.

Inclusion criteria were being male, participating regularly in long-distance running training, and being free of current musculoskeletal pain. All participants were informed about the study's objectives and procedures and provided written informed consent prior to their participation. The study was conducted in accordance with the Declaration of Helsinki and approved by the institutional ethics committee (REPRIN-FOD-171).

Measures

Three-dimensional kinematic data were collected using a BTS SMART-DX Evo motion capture system (BTS Bioengineering, Italy), consisting of eight infrared cameras. Reflective markers were placed according to a modified Helen Hayes protocol to identify gait cycle events and calculate temporal parameters. The following spatiotemporal variables were analysed: Stride time (s), stance time (s), swing time (s), stance phase (%), swing phase (%), cadence (steps/min). Temporal parameters were calculated separately for the right and left limbs, except for cadence, which was considered a global parameter.

Procedures

Participants were recruited through local running clubs. After verifying eligibility criteria and obtaining informed consent, each participant completed a standardized testing session. Prior to data collection, anthropometric measurements were obtained using a measuring tape, including anterior superior iliac spine (ASIS) distance, hip depth, and lower limb length, to ensure accurate marker placement. The motion capture volume was calibrated according to the manufacturer's specifications before each testing session.

Reflective markers were placed according to the modified Helen Hayes marker set implemented in the BTS SMART-Clinic treadmill protocol, which is based on the gait analysis models described by Kadaba et al. (1990) and Davis et al. (1991). Markers were positioned on specific anatomical landmarks of the lower extremities to allow precise identification of running gait cycle events. A schematic representation of the motion capture setup and camera distribution is presented in Figure 1.

A 5-minute warm-up was performed on a treadmill at a self-selected comfortable running speed, followed by an incremental treadmill protocol at three fixed speeds (9, 11, and 13 km/h). At each speed, participants

performed a 2-minute familiarization period followed by 15 seconds of data acquisition. Participants were instructed to run naturally and to avoid consciously modifying their running technique throughout the protocol. For each running speed, gait cycle events were identified using SMARTclinic software (BTS Bioengineering, Italy). A minimum of 12 valid consecutive gait cycles were analysed for each participant. Temporal variables were calculated for each gait cycle and averaged to obtain a representative value for each participant and condition.



Note. Schematic representation of the motion capture setup, illustrating the treadmill positioned at the centre of the capture volume and the peripheral distribution of eight infrared cameras (SMART DX Evo, B TS Bioengineering).

Figure 1. Layout of the motion capture system.

Data analysis

Kinematic data were processed using SMARTclinic software (BTS Bioengineering) and statistically analysed using SPSS (version 26.0, IBM Corp., Armonk, NY, USA). Descriptive analyses were performed, reporting median, mean, and standard deviation for each variable, differentiated by group, limb, and running speed. To evaluate the effects of speed, injury history, and their interaction on the temporal parameters of the running gait cycle, mixed-model repeated measures analyses of variance were conducted, considering speed as the within-subject factor and group as the between-subject factor and Bonferroni-corrected post hoc comparisons. Additionally, non-parametric analyses were performed for between-group comparisons in specific variables using the *Mann–Whitney U* test when appropriate. The level of statistical significance was set at $p < .05$.

RESULTS

Data from 30 runners are presented, with anthropometric characteristics reflecting a typical profile of recreational long-distance runners, within the normal weight range, with a stable and homogeneous distribution of their physical characteristics ($p > .05$), suitable for the execution of the incremental treadmill protocol (Table 1).

Spatiotemporal parameters of the running gait cycle obtained at 9, 11, and 13 km/h are presented in Table 2, differentiated by group (runners with and without a history of knee injury) and by limb (right and left). For each variable, median values as well as mean and standard deviation are reported to characterize the temporal behaviour of the running pattern in both groups. Cadence is presented as a global parameter, as it represents an integrated measure of the running cycle and is not limb-dependent.

Table 1. Characteristics of participants classified as with and without a history of knee injury.

Variable	With Injury History (n = 15)		Without Injury History (n = 15)	
	Media	SD	Media	SD
Age (years)	32.87	9.53	28.53	6.22
Height (cm)	174.87	7.54	172.07	6.38
Weight (kg)	77.20	10.46	72.47	10.47
BMI (kg/m ²)	25.20	2.83	24.40	3.33
ASIS (cm)	28.20	1.57	26.87	1.19
RHD (cm)	13.01	0.91	12.83	1.03
LHP (cm)	13.00	0.93	12.86	1.04
LLR (cm)	90.80	4.72	88.90	4.61
LLL (cm)	90.73	4.62	88.89	4.60

Note: Data are presented as means and SD = Standard Deviation. BMI = Body Mass Index; ASIS = Anterior Superior Iliac Spine; RHD = Right Hip Depth; LHP = Left Hip Depth; LLR = Lower Limb Right; LLL = Lower Limb Left.

Table 2. Spatiotemporal parameters of the running gait cycle at 9, 11, and 13 km/h in runners with and without a history of knee injury.

S (km/h)	Limb	Variable	With Injury History (n = 15)				Without Injury History (n = 15)			
			Mdn	M ± SD	CI 95%		Mdn	M ± SD	CI 95%	
9	Right	Stride time (s)	0.720	0.718 ± 0.036	0.697	0.739	0.710	0.682 ± 0.175	0.586	0.780
		Stance time (s)	0.370	0.364 ± 0.023	0.351	0.378	0.350	0.347 ± 0.026	0.333	0.362
		Swing time (s)	0.380	0.375 ± 0.031	0.358	0.392	0.390	0.392 ± 0.027	0.377	0.407
		Stance phase (%)	50.899	50.899 ± 4.461	48.323	53.474	47.720	47.731 ± 3.443	45.830	49.633
		Swing phase (%)	53.020	52.294 ± 3.643	50.191	54.398	54.250	54.218 ± 2.706	52.719	55.717
	Left	Stride time (s)	0.720	0.721 ± 0.035	0.701	0.742	0.710	0.681 ± 0.176	0.584	0.779
		Stance time (s)	0.370	0.366 ± 0.020	0.355	0.378	0.360	0.351 ± 0.034	0.332	0.370
		Swing time (s)	0.370	0.373 ± 0.030	0.355	0.390	0.390	0.387 ± 0.028	0.371	0.402
		Stance phase (%)	51.140	50.682 ± 4.120	48.303	53.061	49.070	48.601 ± 4.367	46.183	51.019
		Swing phase (%)	52.645	51.728 ± 3.117	49.928	53.527	53.750	53.608 ± 3.479	51.682	55.534
		Cadence (steps/min)	166.500	167.23 ± 7.910	162.662	171.795	168.600	166.20 ± 9.911	160.711	171.689
11	Right	Stride time (s)	0.710	0.705 ± 0.036	0.684	0.725	0.690	0.704 ± 0.059	0.672	0.736
		Stance time (s)	0.320	0.323 ± 0.021	0.311	0.334	0.320	0.318 ± 0.029	0.302	0.334
		Swing time (s)	0.410	0.403 ± 0.032	0.385	0.420	0.410	0.406 ± 0.032	0.388	0.424
		Stance phase (%)	45.840	46.089 ± 4.106	43.815	48.363	45.950	45.372 ± 3.877	43.225	47.519
		Swing phase (%)	58.270	57.140 ± 3.353	55.283	58.997	58.760	57.708 ± 2.885	56.110	59.306
	Left	Stride time (s)	0.710	0.712 ± 0.025	0.698	0.726	0.710	0.706 ± 0.054	0.676	0.736
		Stance time (s)	0.330	0.319 ± 0.030	0.303	0.336	0.320	0.319 ± 0.034	0.301	0.338
		Swing time (s)	0.410	0.407 ± 0.039	0.386	0.429	0.400	0.404 ± 0.030	0.387	0.421
		Stance phase (%)	45.470	44.723 ± 4.446	42.261	47.185	47.000	45.333 ± 3.824	43.215	47.451
		Swing phase (%)	57.300	57.267 ± 4.789	54.615	59.919	57.790	57.325 ± 3.626	55.317	59.333
		Cadence (steps/min)	169.800	169.960 ± 7.152	166.000	173.920	172.8	171.08 ± 13.308	163.710	178.450
13	Right	Stride time (s)	0.680	0.683 ± 0.033	0.665	0.701	0.680	0.692 ± 0.051	0.664	0.720
		Stance time (s)	0.310	0.301 ± 0.020	0.290	0.312	0.290	0.296 ± 0.034	0.277	0.315
		Swing time (s)	0.410	0.403 ± 0.027	0.388	0.418	0.410	0.407 ± 0.051	0.3787	0.4346
		Stance phase (%)	44.360	44.195 ± 2.915	42.581	45.810	42.460	42.830 ± 5.235	39.930	45.728
		Swing phase (%)	60.120	58.982 ± 3.830	56.861	61.103	59.450	58.971 ± 5.935	55.685	62.258
	Left	Stride time (s)	0.680	0.683 ± 0.036	0.663	0.703	0.680	0.693 ± 0.049	0.666	0.720
		Stance time (s)	0.300	0.301 ± 0.013	0.293	0.308	0.280	0.285 ± 0.030	0.268	0.301
		Swing time (s)	0.410	0.405 ± 0.031	0.388	0.422	0.410	0.418 ± 0.046	0.3928	0.4432
		Stance phase (%)	45.040	43.977 ± 2.809	42.422	45.533	41.880	41.115 ± .045	38.682	43.627
		Swing phase (%)	59.260	59.304 ± 4.044	57.064	61.544	59.030	60.170 ± 4.343	57.765	62.575
		Cadence (steps/min)	175.8	176.000 ± 8.254	171.429	180.571	177.000	174.120 ± 11.477	167.764	180.476

Note. Mdn = Median; SD = Standard Deviation; S = Speed. Cadence is expressed as a global parameter of the running cycle.

Overall, descriptive values across the three running speeds showed a consistent and stable temporal pattern of the gait cycle. Stride time remained within a narrow range (0.68–0.72 s), while stance time ranged between 0.29 and 0.37 s in both limbs. The percentages of stance and swing phases showed small variations between speeds (approximately 1–3%), and minimal differences were observed between groups. Cadence increased progressively as running speed increased but remained comparable between runners with and without a history of injury (Table 2).

A mixed-design repeated-measures ANOVA was conducted with speed (9, 11 and 13 km/h) and limb (right and left) as within-subjects factors, and injury status (injured vs. uninjured) as a between-subjects factor. No significant main effects were observed for speed ($F_{(1.05, 29.45)} = 0.66, p = .430, \eta p^2 = .023$); limb ($F_{(1, 28)} = 0.76,$

$p = .392$, $\eta p^2 = .026$); nor of injury ($F_{(1, 28)} = 0.32$, $p = .578$, $\eta p^2 = .011$). Similarly, no significant interactions were found between speed and limb ($F_{(1.78, 49.87)} = 0.50$, $p = .586$, $\eta p^2 = .018$); speed and injury ($F_{(1.05, 29.45)} = 1.22$, $p = .280$, $\eta p^2 = .042$); limb and injury ($F_{(1, 28)} = 0.34$, $p = .567$, $\eta p^2 = .012$); nor for the three-way interaction speed \times limb \times injury ($F_{(1.78, 49.87)} = 0.38$, $p = .661$, $\eta p^2 = .013$). Stance time decreases significantly as running speed increases (very large effect: $\eta p^2 = .846$). The response of stride time to changes in speed was comparable in both groups and in both limbs.

About stance time, the mixed ANOVA revealed a significant main effect of speed on stance time ($F_{(1.68, 46.97)} = 154.36$, $p < .001$, $\eta p^2 = .846$). *Bonferroni-corrected post hoc* comparisons showed that support time decreased significantly as running speed increased, with differences observed between 9 and 11 km/h ($\Delta = 3.78$, $p < .001$), between 9 and 13 km/h ($\Delta = 6.20$, $p < .001$), and between 11 and 13 km/h ($\Delta = 2.42$, $p < .001$). No significant effects were found for limb ($F_{(1, 28)} = 0.40$, $p = .532$, $\eta p^2 = .014$), nor for injury condition ($F_{(1, 28)} = 1.49$, $p = .232$, $\eta p^2 = .051$). Furthermore, the interactions speed \times injury, speed \times limb, limb \times injury and speed \times limb \times injury did not reach statistical significance ($p > .05$). The trend analysis revealed significant linear ($F_{(1,28)} = 278.12$, $p < .001$, $\eta p^2 = .909$) and quadratic ($F_{(1,28)} = 5.42$, $p = .027$, $\eta p^2 = .162$), suggesting that the reduction in stance time as speed increases follows a predominantly linear pattern, albeit with some curvature.

The swing time increased significantly when speed increased from 9 km/h to 11 km/h and remained stable between 11 km/h and 13 km/h. No differences were observed between limbs or between runners with and without a history of knee injury.

However, complementary non-parametric analyses revealed specific between-group differences in stance time. A significant difference was identified in the stance time of the right limb at 9 km/hr, which was greater in runners with a history of knee injury compared to those without ($Z = -2.094$, $p = .037$). Additionally, at a running speed of 13 km/h, the stance time of the left limb was also significantly greater in the injury group ($Z = -2.361$, $p = .018$). No statistically significant differences were observed between groups for stride time, swing time, stance phase, swing phase, or cadence at any of the evaluated speeds ($p > .05$), reinforcing the overall similarity in temporal running patterns between groups.

DISCUSSION

The aim of this study was to compare the temporal parameters of the running cycle between long-distance runners with and without a history of knee injury during an incremental treadmill protocol. Overall, both groups exhibited a comparable overall temporal pattern across the speeds assessed. No differences were observed in stride time, swing time, phase percentages, or cadence, indicating that a history of injury was not associated with a general reorganization of the temporal cycle under the conditions analysed.

The gradual increase in speed induced the hypothesized temporal adjustments in both groups, characterized by a reduction in stride length and ground contact time, as well as an increase in cadence. This behaviour aligns with the described relationship between running frequency and stride length, where speed results from the product of these two variables and their compensatory adjustments (Kapri, Mehta & Singh, 2021; Van Oeveren et al., 2024). The consistent response to the increase in speed suggests that the basic temporal control of the locomotor pattern remains intact in runners with a history of injury.

In the inferential analyses, the mixed models for repeated measures did not reveal any significant main effects or interactions between speed and injury history, indicating that there was no structural modification of the

temporal pattern throughout the incremental protocol. However, nonparametric analyses revealed specific differences in stance time at specific speeds. At 9 km/h, stance time on the right limb was significantly longer in runners with a history of injury, whereas at 13 km/h the difference was observed on the left limb. The emergence of these differences at different speeds and in opposite limbs suggests that the effect associated with injury history does not follow a uniform bilateral pattern, but rather localized temporal adjustments that may manifest under specific mechanical demands. The absence of global effects in the mixed model, together with the presence of specific differences detected through nonparametric analyses, indicates that the adaptations associated with a history of injury were subtle and of small magnitude. This behaviour suggests that the general locomotor pattern may remain stable while specific variations are expressed in the stance phase.

Stance time is a biomechanically significant variable, as this phase involves the greatest interaction between the lower limb and the ground and is when the primary processes of shock absorption and load transfer occur. It has been reported that during running, the patellofemoral joint can experience compressive forces of up to four times body weight, especially during initial contact and load acceptance (Esculier et al., 2015). In this context, small variations in stance duration could represent temporal adjustments associated with load modulation in subjects with a history of injury.

These findings are consistent with previous research suggesting that biomechanical adaptations may persist after musculoskeletal injury. Souza et al. (2023) reported differences in lower-limb movement patterns during running, indicating that injury-related adaptations may be expressed through subtle biomechanical adjustments rather than through global alterations in running mechanics. In the present study, these adaptations were reflected in specific differences in stance time, despite the overall similarity of the temporal running pattern between groups.

Furthermore, recent evidence has shown that specific modifications can occur without a complete reorganization of the locomotor pattern. De Souza Júnior et al. (2024) observed that, following retraining interventions in runners with patellofemoral pain, no significant changes occurred in multiple kinematic variables despite clinical improvement. Taken together, these findings reinforce the idea that the locomotor system can maintain its overall organization while exhibiting discrete adjustments.

From a clinical perspective, identifying specific increases in ground contact time can provide valuable information for runners with a history of knee injuries. Given that a history of injury is one of the most consistent risk factors for recurrence in runners (Van Poppel et al., 2021), a detailed assessment of the stance phase could contribute to biomechanical monitoring during rehabilitation and secondary prevention. However, further studies are needed to confirm these findings.

Among the study's limitations are the absence of direct measurements of ground reaction forces and the calculation of joint moments using inverse dynamics, which prevents the establishment of a quantitative relationship between the observed increase in stance time and the exact magnitude of the joint load. Furthermore, the cross-sectional design does not allow for the establishment of causal relationships between the history of injury and the observed temporal differences. Another limitation of this study was that participants were classified according to their history of knee injury based on self-report, and functional assessment was carried out using the KOOS questionnaire, without a specific clinical diagnosis to identify the type, severity or exact location of the injury. In this regard, future research should incorporate specialised clinical assessments, confirmed medical diagnoses and, where possible, imaging studies or clinical records to improve the accuracy of participant classification. Furthermore, it would be appropriate to differentiate

runners according to the type of knee injury (e.g., patellofemoral pain syndrome, meniscal injury or ligament injury), the time elapsed since the injury and their recovery status, in order to determine whether these characteristics differentially influence the functional and biomechanical variables analysed. Finally, longitudinal studies could help to clarify the relationship between the functional alterations observed and the development or recurrence of knee injuries in runners.

CONCLUSIONS

In conclusion, long-distance runners with a history of knee injury exhibited an overall temporal pattern comparable to that of runners without such a history during an incremental treadmill protocol. However, specific increases in ground contact time were identified at certain speeds, suggesting the presence of discrete temporal adjustments associated with injury history. From a practical perspective, these findings suggest that temporal analysis according to running speed and limb may provide additional information for the biomechanical assessment and monitoring of runners with a history of knee injury. Further longitudinal studies are needed to determine the clinical significance of these adaptations and their relationship with future injury risk.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Carlos Alberto Mendoza Gómez (CAMG), María Cristina Enríquez Reyna (MCER), and Marina Medina Corrales (MMC) participated in the conceptualization of the study, while the methodology and data analysis involved all authors (CAMG, MCER, MMC, Perla Lizeth Hernández Cortés (PLHC), Pedro Gualberto Morales Corral (PGMC), and Luis Enrique Carranza García (LECG). The formal analysis was conducted by CAMG, MCER, and MMC, and data curation was performed by CAMG and MMC. The original draft was written by CAMG and MCER, while the revision and editing of the manuscript, as well as the visualization of the results, involved all authors. Supervisory tasks were performed by MCER, MMC, PGMG, PLHC, and LECG, while project management was handled by CAMG, MCER, and MMC. Finally, funding acquisition was managed by CAMG and MMC. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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CONFLICT OF 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 manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and

readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

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