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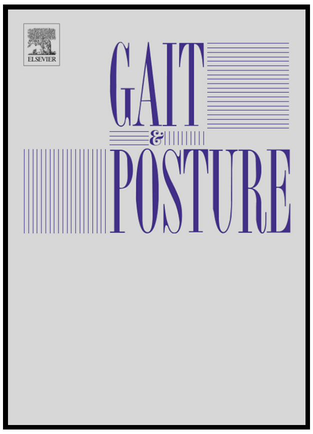

SYNCHRONIZATION PERFORMANCE AFFECTS GAIT VARIABILITY MEASURES DURING CUED WALKING

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Abstract: Background: Incorporating variability within gait rehabilitation offers a promising approach to restore functional capacity. However, it's success requires adequate synchronization, a parameter that lacks report in most of the literature regarding cued gait training. Research question: How changes to synchronization performance during fractal-like and isochronous cueing impacts gait variability measures? Methods: We asked twelve young male participants to walk in synchronization to two different temporally structure cueing (isochronous [ISO] and fractal [FRC]). We have also manipulated the cueing's tempo by increasing and decreasing it by 5% to manipulate synchronization, resulting in six conditions (stimuli [ISO,FRC] x tempo [SLOW, NORMAL, FAST]). The normal condition was set from an uncued trial through the participant's self-paced stride time. Synchronization performance (ASYNC) and gait variability (fractal scaling and coefficient of variation) were calculated from stride time data (-ISIs,CV-ISIs). Repeated measures analysis of variance or Aligned Rank Transform were conducted to determine significant differences between metronome tempo and stimuli for the dependent variables. Results: Our results showed a FAST tempo decreases synchronization performance (ASYNC) and leads to lower -ISIs, for both ISO and FRC stimuli. This indicates that when an individual exhibits poor synchronization during cued gait training, his/her gait variability patterns will not follow the temporal structure of the presented metronome. Specifically, if the individual poorly synchronizes to the cues, the gait patterns become more random, a condition typically observed in older adults and neurological patients, which runs contrary to the hypothesis when using fractal-like metronomes. Significance: This study provides supporting evidence that measuring synchronization performance in cued training is fundamental for a proper clinical interpretation of its effects. This is particularly relevant for the recent and ongoing clinical research using fractal-like metronomes since the expected gait patterns are dependent on the synchronization performance. Randomized control trials must incorporate synchronization performance related measures.

Introduction

Gait rehabilitation often uses external cues to restore gait patterns. This approach, also known as sensorimotor synchronization [1], has demonstrated positive effects in the gait patterns of older adults [2] and neurological patients [2-8]. However, other studies failed to show gait improvements [9-11], questioning the usefulness of external cues in gait rehabilitation. The reported discrepancies in gait improvements are likely to have different causes, e.g., the population or pathology under investigation, the cueing modality, the temporal structure of the cues, or the frequency used on the cues. In the clinic, the cues are typically presented as markers on the floor to step in or auditory cues to step on time, mostly aiming stride time and/or stride length. Regardless, a fundamental and crucial aspect commonly neglected is cue synchronization, also previously pointed out as a major limitation in clinical trials [6,12]. Reporting synchronization performance to the cues would allow a more robust and appropriate interpretation of cued gait rehabilitation effects. This would ultimately lead to the identification of which approach better suits different populations.

The understanding of synchronization performance is particularly relevant given the growing body of research suggesting the incorporation of variability in the cues' temporal structure [13-19]. These authors propose that the temporal/spatial distance between cues should not be fixed, but rather with non-random variations. Specifically, the cues should be presented in a fractal-like pattern. This innovative cue presentation relies on previous studies that found gait patterns of healthy individuals to exhibit fractal-like patterns, whereas older adults and neurological patients presented deterioration of these patterns [16,20,21]. Importantly, these fractal-like patterns are thought to represent a 'complex' system that contains a certain amount of 'structured' variability enabling system's adaptability. Conversely, a loss of complexity as in the case of ageing, either too much or too little variability, represents an unhealthy system with reduced capacity to adapt to environmental constraints [22,23]. Importantly, although extensive literature supports the loss of complexity to altered gait control (i.e., loss of complexity hypothesis), others associated to motor noise [24,25].

Given the lack of research regarding synchronization performance, it becomes questionable whether positive improvements in gait parameters while using isochronous cueing are misleading. Thus, it is possible that decreased synchronization to isochronous cues may lead to fractal-like patterns by chance during gait, and the improvements observed should not be attributed to isochronous cueing. However, since this would occur by chance, it is also plausible to consider it would lead to changes in the opposite direction. The manipulation of other gait parameters through the increase and decrease of cues' frequency was previously attempted [26,27]. Significant effects of different cueing frequencies on spatiotemporal gait parameters on both treadmill and overground walking have been reported [26,27]. Decrease of cueing frequency resulted in the increase of step length when walking on a treadmill, whereas the increase of the cueing frequency produced an increase in both cadence and gait speed when walking overground in Parkinson patients. [26]. However, it remains to be investigated if synchronization performance affects gait variability measures. If synchronization performance does affect gait variability, the adjustment of cueing parameters, such as frequency, should be considered. In fact, frequency adjustment in the presentation of the cues was recently suggested [28].

The present study investigated the effects of cueing tempo (normal, slow and fast) on synchronization performance and gait variability measures during two cued walking tasks (isochronous and fractal). We hypothesized that a faster tempo would worsen synchronization and, hence, would alter gait variability.

Methods

Participants

Twelve male participants (22.3±3.6 years, 1.74±0.06 m, 69.4±7.8 kg) were included in this study. Participants had no medical history of cardiovascular or metabolic disease/disorders nor a history of musculoskeletal disorders in the past six months. Participants signed an informed consent that the Institutional Review Board previously approved.

Experimental Procedures

For preferred walking speed (PWS) determination, participants were asked to start walking on the treadmill and the speed was gradually increased in increments of 0.1 km/h. Participants indicated when comfortable with the treadmill's speed. Once comfortable with the speed, additional increments of 0.1 km/h were added until the participant indicated it was becoming "too fast to be comfortable". The same procedure was conducted to decrease the speed until the participant referred it to be "too slow to be comfortable". This procedure was repeated three times in each direction, and the average of the six measures was considered as PWS. The participants were then allowed to remain walking at the PWS speed for familiarization for approximately 2 minutes.

The first trial was a self-paced uncued trial, needed to calculate preferred stride time. This trial's stride time was used to design individualized visual stimuli for 6 randomized cued trials: 3 tempos [SLOW, NORMAL, FAST] x 2 types of stimuli [Isochronous – ISO; Fractal – FRC]. The six randomized trials were distributed amongst two sessions. Each trial lasted 10-minutes, and a minimum of 5-minutes resting period was given between trials. For the NORMAL trials, the stride time determined from the self-paced trial was used, while for the SLOW and FAST, a 5% decrease or increase was applied to stimulus' tempo, respectively.

The visual cues were provided via a moving horizontal bar moving up and down [18], projected on a flat screen in front of the participant. Participants were instructed to synchronize their right heel strike to the top of the moving bar's path. The moving indicator turned red when reaching the top of the display. The FRC cueing was generated using an approximation of a -10 dB/decade filter with a weighted sum of first-order filters. This cues' structure was previously validated using Detrended Fluctuation Analysis (DFA) – FRC: $\alpha = 1$, pink noise [18]. It was scaled using the mean and standard deviation of each participant's self-paced stride-time. This scaling generated a set of individual-specific cueing but also maintained the consistency of cueing patterns across participants. The ISO cueing was generated using each participant's mean self-paced stride-time and a standard deviation of zero. A miniaturized triaxial accelerometer (Plux Biosignals, Portugal), placed at the lateral malleoli, was used to determine gait events. Acceleration data were collected at 1000Hz.

Data Analysis

The first 15-seconds of each trial were discarded prior to analysis to avoid transient effects of familiarization to the stimulus. A 4th order, zero lag low-pass Butterworth filter with a cutoff frequency of 20Hz was applied to the accelerometer signal. A custom MATLAB code was used to determine inter-stride intervals (ISIs), defined as the time difference between two consecutive heel strikes of the same foot. Outliers that fell outside ±2.5 standard deviations from the mean were removed from the time series. After outliers were removed, the coefficient of variation (CV) and fractal scaling were calculated for each ISI time series. CV was used as a measure of the magnitude of variability, while fractal scaling was used as a measure of the temporal structure of variability. Asynchronies (ASYNC) were calculated as the time difference between the heel strike and the cue. A negative value indicates that the heel strike occurred before the stimulus. The mean asynchronies ($ASYNC_{mean}$) was calculated as a global indicator of synchronization performance. In addition, we calculated an asynchronies ratio ($ASYNC_{ratio}$). Specifically, we calculated the percentage of negative asynchronies (i.e., anticipatory), multiplying by 100 the quotient between the number of negative asynchronies and the total number of asynchronies ($\frac{ASYNC_{negative}}{ASYNC_{total}} * 100$). For example, an $ASYNC_{ratio}$ of 80% indicates that 20% of the asynchronies presented a reactive nature, i.e., the heel strike occurred after the cue. This is an important complementary parameter to appropriately interpret $ASYNC_{mean}$.

Detrended Fluctuation Analysis (DFA) was used to determine the fractal-scaling exponent (α) for the ISI time series (α-ISIs). α quantifies the presence of the long-range correlations found in a physiological time series. The time-series is first detrended. Then, DFA integrates a time series divided into window sizes of length *n*. In each window, a least squares line of best fit is calculated. The data is then detrended by subtracting the integrated time series from the least squares line. The root mean square is calculated for each window to determine the magnitude of fluctuation, and is summed for the entire time series, F(n). This process is repeated for a range of window sizes to determine the associated magnitudes of fluctuation for each window size. Next, the log F(n) is plotted against log n (the root mean square is plotted against the window sizes), and the slope of this line is the α-scaling exponent. α values greater than 0.5 indicate a positively persistent long-range correlation. This means that increases tend to be followed by increases and decreases tend to be followed by decreases. α values less than 0.5 indicate anti-persistent correlations, which mean that increases tend to be followed by decreases, and vice-versa. Window sizes of 16 to N/8 were used in the ISI analysis, where N is the length of the data.

Statistical Analysis

Statistical analyses were conducted using R [29] with alpha level set a priori 0.05. Normality of data was confirmed using a Shaprio-Wilk's test ($p<0.05$), skewness and kurtosis values, and visual investigation of histograms, normal Q-Q plots, and box plots and descriptive data were calculated. Two dependent measures met the assumption of normality ($ASYNC_{mean}$, and α-ISIs); whereas two dependent measures did not meet the assumption of normality ($ASYNC_{ratio}$ and CV-ISIs). Repeated measures analysis of variance (ANOVA) were conducted to determine significant differences between cueing tempo and stimuli conditions for $ASYNC_{mean}$ and α-ISIs. Aligned Rank Transform (ART) were conducted for $ASYNC_{ratio}$ and CV-ISIs [30-33]. Where results were significant, pairwise comparisons with Bonferroni corrections were conducted. R packages included in the analyses were: afex [34], ARTool [35], dplyr [36], emmeans [37], grateful [38], openxlsx [39], plyr [40], and rstatix [41].

Results

Mean Asynchronies ($ASYNC_{mean}$)

As for mean $ASYNC_{mean}$, no Stimuli x Tempo interaction was not observed ($F_{(1.07,10.69)}$ = 2.92; p = 0.115; η_p^2 = 0.226). No main effect was observed for Stimuli ($F_{(1,10)}$ = 0.662; p = 0.435; η_p^2 = 0.062), but a significant main effect was found for Tempo ($F_{(1.64,16.38)}$ = 37.08; p < 0.001; η_p^2 = 0.788). Pairwise comparisons revealed NORMAL (-90 ± 15ms) to be higher than SLOW (-154 ± 21ms, p=0.001) and lower than FAST (-33 ± 17ms, p=0.006) – Figure 1A; and SLOW was lower than FAST (p<0.001).

[insert Figure 1 here]

Asynchronies' Performance Ratio ($ASYNC_{ratio}$)

In terms of the $ASYNC_{ratio}$, we have observed a significant Stimuli X Tempo interaction ($F_{(2,55)}$ = 5.994; p = 0.004). Table 1 presents all the multiple comparison between the six conditions. No main effect was observed for Stimuli ($F_{(1,55)}$ = 2.460; p = 0.123), but a significant main effect was found for Tempo ($F_{(2,55)}$ = 32.336 p < 0.001). Pairwise comparisons revealed NORMAL (89 ± 2%) had a greater percentage of anticipatory strides than FAST (62±7, p = 0.036), but less than SLOW (97 ± 2%, p = 0.005); and FAST showed significantly less than SLOW (p=0.001) – Figure 1B.

[Insert Table 1 here]

Inter Stride Intervals (ISIs)

In terms of α-ISIs, no Stimuli x Tempo interaction was observed ($F_{(1.97,21.66)}$ = 0.28; p = 0.758; η_p^2 = 0.004). A significant main effect was found for both Stimuli ($F_{(1,11)}$ = 26.52; p < 0.001; η_p^2 = 0.548) and Tempo factors ($F_{(1.73,19)}$ = 6.98; p = 0.007; η_p^2 = 0.114). Pairwise comparisons showed that α-ISIs was higher during FRC (0.76±0.18) than ISO (0.43±0.14, p < 0.001, Figure 2). For the Tempo factor, pairwise comparisons showed α-ISIs during FAST (0.52±0.23) to be significantly lower than NORMAL (0.65±0.22, p=0.030); while no differences were observed between SLOW and NORMAL (p = 0.792); nor SLOW and FAST (p = 0.058).

[insert Figure 2 here]

Regarding CV-ISIs, no Stimuli x Tempo interaction was observed ($F_{(2,55)}$ = 0.150; p = 0.861). Likewise, no main effect was found for Tempo ($F_{(2,55)}$ = 0.151; p = 0.860). A significant main effect was observed for Stimuli ($F_{(1,55)}$ = 53.281; p < 0.001), where CV-ISIs was found to be higher in FRC (2.99 ± 0.44%) compared to ISO (1.72 ± 0.15%).

Discussion

This study aimed to investigate how changing the cueing tempo affects synchronization performance and gait variability measures during cued walking. We experimentally manipulated the synchronization by increasing and decreasing the cueing tempo by 5%. Additionally, this was tested while the participants walked to both to an isochronous and a fractal-like cues. We hypothesized that a faster tempo would affects gait variability because of a decreased synchronization, regardless of the cueing condition (FRC or ISO). The findings supported our hypotheses. Overall, we have found that decreased synchronization performance altered gait variability patterns.

First and foremost, it is important to emphasize that we have successfully affected synchronization performance through our experimental design (i.e., manipulating the cueing's tempo). This is supported by our results related to the asynchronies ($ASYNC_{mean}$ and $ASYNC_{ratio}$). On the one hand, we have observed that by slowing the cueing's tempo, the asynchronies negatively increased than at normal tempo (i.e., the individuals stepped earlier). Conversely, the asynchronies negatively decreased (i.e., closer to 0) when the cueing's tempo was faster compared to the normal tempo condition. These results should be carefully interpreted. Mean asynchronies close to 0 do not necessarily represent a better synchronization. Individual data presented in Figure 1A shows that some participants exhibited positive mean asynchronies during the fast condition, indicating that they used a more reactive type of strategy rather than anticipatory. Therefore, we have added a complementary parameter to provide us with more details in terms of the synchronization strategy – $ASYNC_{ratio}$ (Figure 1B). Here, we globally demonstrated that when the cueing tempo was 5% faster, there was a decrease in the number of anticipatory strides compared to normal and slow tempo conditions (i.e., more reactive strides). Overall, these results suggest that either increasing or decreasing the cueing's tempo affects synchronization performance, although in different directions: larger distance to the cues while keeping an anticipatory strategy (slow condition) or transitioning to more reactive strategy (fast condition).

Regarding gait variability measures (α-ISIs), the results indicate that changes in synchronization similarly affected both walking to an isochronous and a fractal-like cueing conditions. However, we did not observe an increase in α-ISIs during isochronous cueing when the synchronization worsens. This means that, high α-ISIs are unlikely to emerge during isochronous cueing. Not surprisingly, α-ISIs was higher during the fractal-like cued condition compared to isochronous, similarly to previous reports [15-18]. It is noteworthy the decrease in α-ISIs during the fast tempo condition, regardless of the cueing condition used. This is particularly important for those considering introducing fractal patterns within cueing systems [13-19]. If the cueing is not properly adjusted to the individual's characteristics (e.g., self-paced speed, self-preferred stride frequency, etc.), there is a greater likelihood of worse synchronization performance. In other words, we can be observing unexpected changes in gait variability measures because the training is not focused on optimizing synchronization performance in the first place. Specifically, an individual walking to fractal-like cues is expected to present gait variability with a fractal scaling between 0.8-1.0 [18,42], but if the synchronization performance is decreased, it can result in substantially lower α values, which is contradictory to the aim of the intervention. Our results support this rationale by exhibiting a decrease in fractal scaling of gait patterns when the cueing tempo was faster than normal. For magnitude measures of variability (CV), we found differences between the isochronous and fractal conditions. Although this is an important parameter of gait control, we believe the differences observed are not physiologically meaningful considering the 1.27% absolute difference. In addition, no effects from tempo changes were observed at the magnitude of variability indicating that synchronization appears not to affect this gait variability measure. Synchronization performance is likely one of the major reasons clinical trials in cued walking often set the cueing's tempo at under the self-preferred stride frequency [11,43,44], although research in the field severely lacks reporting synchronization related outcomes.

Although conducted in healthy young adults, some of our findings might have important implications to older adults' gait training. Specifically, the results related to the fast tempo condition that led to lower values of variability in the gait patterns. Older adults are known to a lower rate of information processing that typically results in slower motor response and longer reaction times [45]. Therefore, if older adults are instructed to match the cues and these are set at 100% of their self-preferred stride time, there is a likelihood of a greater number of reactive strides, as observed in our fast conditions in young adults. However, Vaz et al. [28] reported that older adults presented the expected fractal values when walking at their self-preferred stride frequency during cued trials. Importantly, the present study took place on a treadmill where the walking speed is fixed, while conducted overground in Vaz and colleagues' study, during which the walking speed can fluctuate. Although not reported, it is likely that the walking speed during the cued trials was not the same as during the uncued trial. This interpretation is certainly speculative and should be carefully discussed given the aging related changes in gait go beyond this simplistic analysis (e.g., automatic processes are also affected). Despite the need for further investigation to the older adults' gait, the present study's findings support it by showing no differences in gait variability patterns between normal and slow tempo conditions. Therefore, slowing the cueing when training older adults will most likely be beneficial, as it will decrease task's difficulty without compromising gait variability.

Conclusion

This study showed that decreased synchronization performance alters gait variability patterns. Importantly, when the synchronization performance was significantly affected, the gait variability measures were equally negatively affected.

This is particularly relevant for the recent and ongoing clinical research using fractal-like cues since the expected gait patterns are dependent on the synchronization performance. We presented here that if the individual poorly synchronizes to the cues, the gait patterns become more random, a condition typically observed in older adults and neurological patients, which runs contrary to the hypothesis when using fractal-like cues. Thus, this study provides supporting evidence that measuring synchronization performance in cued gait training is fundamental for a proper clinical interpretation of its potential effects. In particular, randomized control trials must incorporate asynchronies measures to quantify such synchronization performance.

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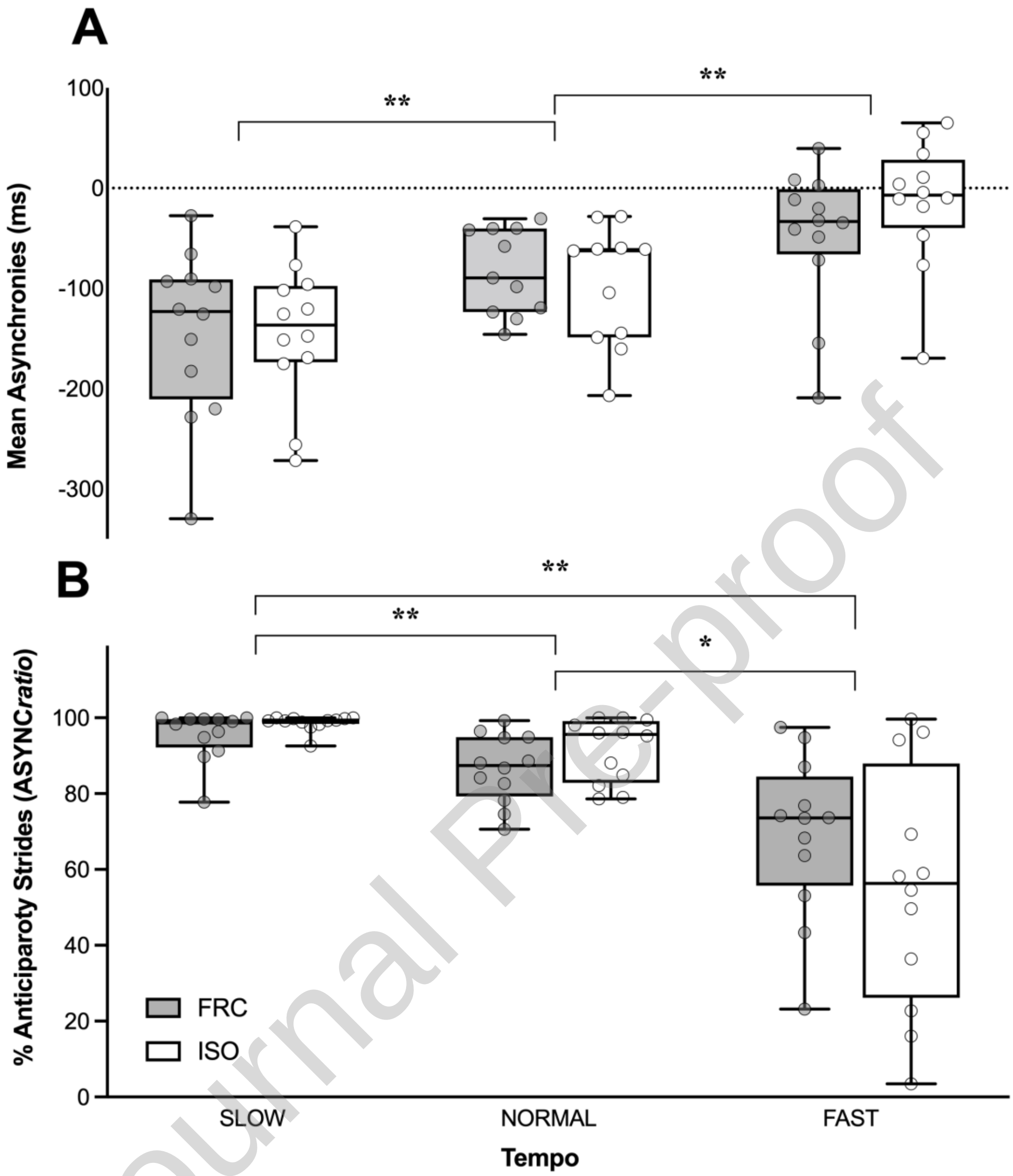

Figure 1. A) The mean asynchronies ($ASYNC_{mean}$) from the three tempo conditions (SLOW, NORMAL, FAST) and two cueing conditions: isochronous (ISO) and fractal (FRC). Grey bars represent the FRC condition; white bars represent the ISO condition. Data are presented as Mean and 95% of Confidence Intervals. The individual data points represent each participant value. ** indicates $p<0.01$. B) The percentage of Anticipatory Strides ($ASYNC_{RATIO}$) for the three tempo conditions (SLOW, NORMAL and FAST) and two cueing conditions: ISO and FRC. Grey bars represent the FRC condition; white bars represent the ISO condition. Data are presented as Mean and 95% of Confidence Intervals. The individual data points represent each participant value. * indicates $p<0.05$. ** indicates $p<0.01$.

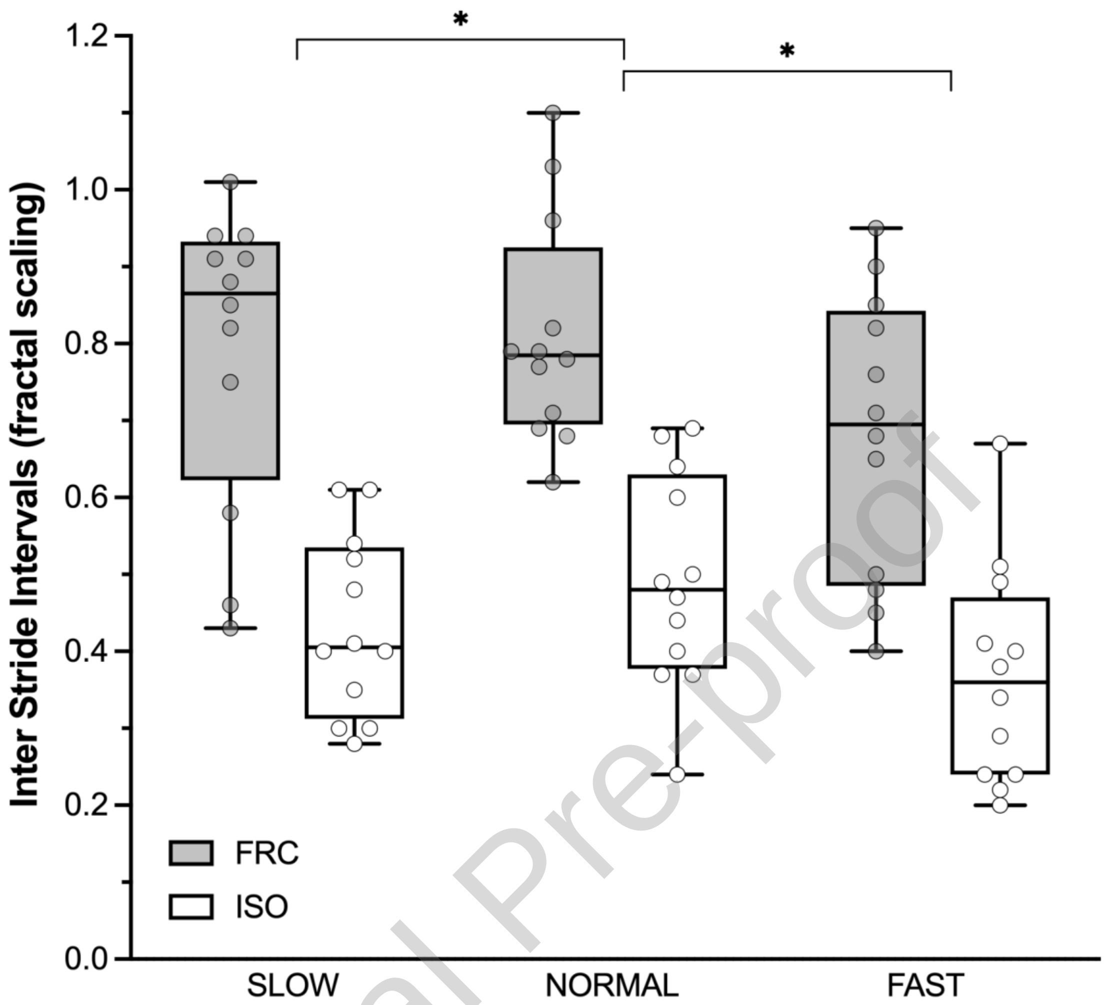

Figure 2. The fractal scaling from the Inter Stride Intervals (α-ISIs) for the three tempo conditions (SLOW, NORMAL and FAST) and two cueing conditions: isochronous (ISO) and fractal (FRC). Grey bars represent the FRC condition; white bars represent the ISO condition. Data are presented as Mean and 95% of Confidence Intervals. The individual data points represent each participant value. * indicates p<0.05.

Table 1. P-values from multiple comparisons for $\mathrm{ASYNC}_{\mathrm{ratio}}$. Significant differences are highlighted in bold. + indicates the condition presented as row showed higher $\mathrm{ASYNC}_{\mathrm{ratio}}$; - indicates the condition presented as row showed higher $\mathrm{ASYNC}_{\mathrm{ratio.}}$ Note that each pairwise comparison should be read as row-column.

		Isochronous			Fractal		
		slow	*normal*	*fast*	*slow*	*normal*	*fast*
onous	*slow*	-	**0.031** (+)	< **0.001** (+)	-	-	-
	normal	-	-	< **0.001** (+)	-	-	-

	fast	-	-	-	-	-	-
Fractal	*slow*	0.393	0.336	**< 0.001** (+)	-	**0.005** (+)	**< 0.001** (+)
	normal	**< 0.001** (-)	0.193	**0.031** (+)	-	-	0.059
	fast	**< 0.001** (-)	**< 0.001** (-)	0.717	-	-	-

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

Highlights

- Reduced synchronization in fractal-like metronome alters gait variability patterns.
- Synchronization performance in cued walking is affected by the metronome's tempo.
- Synchronized walking to a faster metronome increases the number of reactive strides.
- Appropriate synchronization maintains the metronome structure on the gait patterns.