Gait & Posture 70 (2019) 376–382

Contents lists available at ScienceDirect

Gait & Posture

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

Full length article

# Years of running experience influences stride-to-stride fluctuations and adaptive response during step frequency perturbations in healthy distance runners

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ARTICLE INFO

*Keywords:*
Cadence
Long-range correlation
Stability
Adaptability
Novice

ABSTRACT

*Research question:* The current study investigated stride-to-stride fluctuations of step rate and contact time in response to enforced step frequency perturbations as well as adaptation and de-adaptation behavior.
*Methods:* Forty distance runners ran at a self-selected speed and were asked to match five different enforced step frequencies (150, 160, 170, 180, and 190 beats per min). The influence of experience was explored, because running is a skill that presumably gets better with practice, and increased years of running experience is protective against injury. Detrended fluctuation analysis was used to determine the strength of long-range correlations in gait fluctuations at baseline, during the perturbation, and post-perturbation. Adaptive response was measured by the ability to match, rate of matching, and aftereffect of step frequency perturbations.
*Results:* The structure of stride-to-stride fluctuations for step rate and contact time did not change during the perturbation or post-perturbation compared to baseline. However, fluctuations in step rate were affected by the level of perturbation. Runners with the most experience had a less persistent structural gait pattern for both step rate and contact time at baseline. Highly experienced runners also demonstrated the best adaptive response. They better matched the enforced step frequency, reached the enforced step frequency sooner, and returned to preferred step frequency more quickly following removal of the perturbation.
*Significance:* These findings indicate baseline locomotor flexibility may be beneficial to achieve task demands and return to a stable state once the task is complete. Increased locomotor flexibility may also be a contributing factor for reduced injury risk in experienced runners.

## 1. Introduction

Running is a complex form of locomotion that when performed for sport or exercise often results in musculoskeletal injury. A multitude of risk factors for injury have been explored [1]. However, a clearer understanding of injury etiology has not been generated. The ambiguity surrounding injury development may arise from the prevailing focus on traditional kinematic and kinetic factors, which are components to but are not the *final output* of these complex system interactions. For instance, injury rates are higher among less experienced runners [2–4]. However, studies exploring biomechanical measures associated with injuries (e.g., peak hip adduction angle or vertical ground reaction force loading rate) have found no significant differences across experience level [5,6]. This suggests that factors beyond mechanics may increase injury susceptibility in less experienced runners. As runners gain experience, they may develop motor control strategies that optimize task performance while preserving motor flexibility that afford effective response to changing environmental demands or internal constraints. With respect to injury, these developed strategies may help to redistribute loading across musculoskeletal tissues or reduce the amount of accumulated loading on musculoskeletal tissues, thus reducing injury susceptibility. Therefore, there is a growing interest in understanding motor control strategies of system stability and adaptability in relation to running-related injury risk [7].

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https://doi.org/10.1016/j.gaitpost.2019.02.034
Received 17 May 2018; Received in revised form 31 January 2019; Accepted 26 February 2019

Stability of human movement, as viewed through the lens of dynamical systems theory, can be characterized by the ability of the system to rapidly return to its original, or preferred state (i.e., attractor state) in response to perturbations [8]. Adaptability of the system permits movement fluctuations around its preferred state while also allowing for discovery of new movement patterns that better optimize function and/or achievement of movement goals [8]. Further, preferred states, or movement patterns, are often associated with minimal energy expenditure [9,10] and reduced joint loading [11,12], both of which reduce the risk of injury. In a practical sense, quick response to unpredictable task demands (e.g., altering step pattern to evade crack in sidewalk) would be necessary to avoid traumatic injuries, while an efficient return to preferred state following a non-mechanical perturbation appears to be necessary to avoid compromised running economy or cumulative joint loading stress. Therefore, adaptation to an external perturbation and subsequent de-adaptation (i.e., return to preferred state) following removal of the perturbation represent two useful measures of system stability within the running context.

System stability is not readily captured by discrete joint angles or averaged spatiotemporal measures, but rather by the structure of gait patterns. Stride-to-stride fluctuations in gait patterns have been used to describe global system stability [13,14]. Detrended fluctuation analysis (DFA) is a common statistical method for analyzing stride-to-stride fluctuations and has been applied to movement patterns of individuals at risk for falls [15,16] and of individuals exhibiting motor deterioration due to aging or disease [17,18]. Peng and colleagues provide an excellent treatment of DFA methodology [19]. In short, DFA characterizes the statistical persistence, also referred to as long-range correlation, of a time-series and expresses it through a single value, α. α = 0.5 indicates no persistence (i.e., white noise); α < 0.5 indicates anti-persistent correlation, in which deviation in one direction is statistically more likely to be followed by deviation in the *opposite* direction; and α > 0.5 indicates persistence, with deviation in one direction statistically more likely to be followed by deviation in the *same* direction.

Assessing global system stability by examining the structure of a time series can elucidate motor system control and regulation processes [20]. Changes in the structure of gait cycle parameters, particularly in response to a stressor or perturbation to the system, can provide insight into functional adaptability and signal increased risk of musculoskeletal injury. Long-range correlations are present in stride and step parameters for both walking [21] and running [22,23], as well as stride indices [24] and ground reaction forces [25] during running. Moreover, the structure of these parameters during running has been shown to be influenced by fatigue [24,26], footwear [24,27], injury [26,28], and speed [28,29]. Unfortunately, results of the aforementioned studies were varied and did not advance knowledge regarding the sensitivity of α to indicate positive or negative motor system function. A potential reason for the varied results of those studies was the choice of control parameter. For changes in motor system function to be elicited, the control parameter must be one in which the neuromotor system is sensitive to scale changes. While changes in speed will result in coordinative pattern changes (i.e., walk-to-run) there must a large scaling up or down for the motor system to respond. Similarly, for coordinative patterns to significantly shift, a drastic change in footwear characteristics may be necessary. Step frequency appears to be a suitable parameter to perturb to examine system stability. Step frequency is a tightly controlled gait parameter. That is, runners typically prefer to alter stride length or speed before step frequency. When step frequency is modified, the range of modification is generally small ( ± 4%) [30]. Moreover, small changes in step frequency ( ± 5%–10%) have been shown to alter biomechanical and muscle activation patterns in runners [31–33].

Therefore, the primary purpose of this study was to examine the extent to which α changes in response to enforced step frequency perturbations and whether this change was associated with adaptive response. We hypothesized that long-range correlations would weaken in the presence of enforced step frequencies and return to baseline once the perturbation was removed. Additionally, because running is a motor skill and presumably can be learned or mastered over time, our secondary purpose was to explore the influence of running experience on α values and adaptive response.

## 2. Methods

### 2.1. Participants

Forty distance runners (38.6 ± 10.4 years; range: 18–54) participated in this study. Runners were healthy and free of musculoskeletal injury for the 12 months prior to data collection. Running experience to suggest groups were chosen quasi-arbitrarily. There is some evidence that runners with three or less years have a higher odds ratio for running-related injury [34]. Therefore, participants were included in the novice group if they had 3 or less years of distance running experience, intermediate runners were those who had between 4 and 9 years of distance running experience, and experienced runners had 10 years or greater of distance running experience. Distance running was defined as running 5 km or more in a single session. All participants were currently running at least 19 km per week with their shortest run being at least 5 km. Runners were excluded if they had a lower extremity surgery within the last 6 months, wore custom or over-the-counter orthotics, or used a prosthetic device. Each participant provided written informed consent before involvement in the study. Data were collected following a protocol approved by the Institutional Review Board at the University of Michigan.

### 2.2. Experimental protocol

Participants ran on a treadmill in a laboratory setting at a self-selected speed that was representative of a comfortable training pace. Self-selected speed was determined using a pre-defined protocol [23]. Following the warm-up period, participants performed a run for five minutes during which baseline data were collected. Subsequently five external perturbation trials were performed in randomized order. Participants were instructed to match their footfalls to the audible metronome beat as best they could and return to their normal running pattern once the metronome had ceased. Each running trial began with one minute in silence before an audible metronome beat was played. The metronome played for three minutes and was washed out by white noise that lasted for one minute. Participants then ran for three minutes in silence before the trial ended. Neither onset time nor frequencies of the metronome beat were disclosed to the participant, and the frequency of the beats was randomized. The audible metronome beat was played through a monitor located in front of the treadmill. The five levels of enforced step frequency perturbation were 150, 160, 170, 180, and 190 beats per minute (bpm). All running was performed on a pressure-sensing treadmill (h/p/cosmos, Zebris Medical GmbH, Isny, Germany). Underfoot pressure was collected at 120 Hz and used to calculate vertical ground reaction force (vGRF) data.

### 2.3. Data analysis

Spatiotemporal measures were calculated using vGRF values from the instrumented treadmill. Foot contact and toe-off were identified when vGRF exceeded or fell below 5 N, respectively, and were used to determine spatiotemporal variables.

To determine long-range correlations, each time series was integrated to form an accumulated sum. Next, the integrated time series was sectioned into non-overlapping bins with a length of *n* strides. For each bin, a least squares line was fit to the data to represent the local trend. The entire integrated time series was detrended by subtracting the local trend in each bin. This was performed to reduce the influence of nonstationarities present in the time series. A root-mean-square fluctuation [F($n$)] of the integrated and detrended time series was then calculated by taking the standard deviation of the residuals of a linear regression fit to the integrated time series for each bin. This calculation was repeated across all bin sizes. For complete description of detrended fluctuation analysis calculation, see Dingwell et al. [21].

The integrated time series ($N$) is thought to be self-similar if the fluctuations at different observation windows [F($n$)] scale as a power law with the window size ($n$). The coefficient (α) relating [F($n$)] with $n$ on a logarithm scale was used to assess the degree of long-range correlations [17]. Persistent long-range correlations across all times in a time-series produce a scaling exponent α = 1.0. Conversely, anti-persistent or unpredictable stride-to-stride fluctuations are characterized by a scaling exponent α = 0.5 [35]. Persistent long-range correlations with slow stride-to-stride changes and "random drifts" in the time-series exhibit a scaling exponent α = 1.5 [14,35]. The within and between day intra-class correlation coefficients for α are 0.91 and 0.77, respectively [36].

Mean, SD, and α were calculated for step rate and contact time for baseline, perturbation, and post-perturbation periods. Our primary outcome variables of interest were α of step rate and α of contact time.

The rates of adaptation and de-adaptation for each step frequency perturbation level were quantified as the time required for each subject to reach a plateau in step frequency. For time to plateau during the perturbation, the last 30 s of metronome period were used to calculate mean ± 1 SD step frequency and used to define the plateau range, where the beginning of the plateau was considered the first point at which five consecutive strides fell within plateau range. The time to plateau post-perturbation was calculated in the same fashion. The ability of the subject to match the enforced step frequency was calculated as the difference between the mean step frequency during the metronome period and the enforced step frequency. Positive values indicated the runner had a higher step frequency than prescribed. Step frequency drift was defined as the difference between the participant's pre-metronome (preferred) and post-metronome step frequencies.

### 2.4. Statistical analysis

Linear regression was used to determine differences in baseline α values and adaptive responses among running experience groups. A generalized linear mixed model approach was used to test whether α values changed in response to a step frequency perturbation and the extent that experience influenced changes in α. Running speed, enforced step frequency perturbation levels, and preferred step frequency were controlled for in the model. A Pearson correlation coefficient test was used to determine the association between adaptation or de-adaption times and α values. All statistical analyses were performed using Stata 14 (StataCorp, College Station, Texas). Statistical significance was set *a priori* (alpha = 0.05).

## 3. Results

Data from two participants were excluded from analysis, because it was discovered after enrollment that neither met the inclusion criterion for running volume. Participant characteristics can be found in Table 1.

### 3.1. Perturbation: α values and adaptive response

There was not a significant main effect of perturbation on step rate α ($ß = -0.006$, $P = 0.39$; Fig. 1) or contact time α ($ß = -0.002$, $P = 0.61$; Fig. 2) after accounting for enforced step frequency levels, velocity, and preferred step frequency. However, contact time α was substantially higher during the perturbation period ($ß = 0.012$, $P = 0.07$) compared to post-perturbation. The level of enforced step frequency was a significant main effect for step rate α ($ß = -0.023$, $P = 0.005$) but not contact time α ($ß = -0.024$, $P = 0.21$) (Table 2). Step rate α during an enforced frequency of 150 bpm was significantly higher ($P = 0.01$) while 170 bpm was significantly lower ($P = 0.04$) from baseline. Higher step rate α was significantly associated and faster time to plateau ($r = 0.18$; $P = 0.01$) and time to reach enforced step frequency ($r = 0.35$; $P < 0.001$). Contact time α was not significantly associated with time to plateau ($r = 0.02$, $P = 0.76$) or time to reach enforced step frequency ($r = 0.08$, $P = 0.5$). Adaptive response during perturbation period for each enforced step frequency perturbation level can be found in Table 3.

**Table 1**
Participant characteristics.

| | Novice n = 10 | Intermediate n = 11 | Experienced n = 17 |
|---|---|---|---|
| **Personal Characteristics** | | | |
| Age (years) | 34.9 ± 8.5 | 30.0 ± 11.0 | 39.7 ± 9.7 |
| Body Mass (kg) | 66.4 ± 10.2 | 70.7 ± 11.7 | 75.2 ± 11.3 |
| Height (m) | 65.7 ± 5.7 | 69.3 ± 3.6 | 70.1 ± 4.0[a] |
| Reported Pace (m/s) | 3.1 ± 0.4 | 3.5 ± 0.3[a] | 3.3 ± 0.3[a] |
| Running experience (years) | 1.9 ± 0.8 | 5.6 ± 1.6[b] | 17.3 ± 8.2[a] |
| Relative experience (yrs/age) | 0.05 ± 0.02 | 0.2 ± 0.1 | 0.4 ± 0.2 |
| **Training Habits** | | | |
| Running days per week | 4.4 ± 1.2 | 4.6 ± 1.5 | 4.5 ± 1.1 |
| Running months per year | 9.6 ± 3.2 | 10.8 ± 1.5 | 11.2 ± 1.3 |
| Running volume per week (km) | 32.5 ± 14.6 | 51.5 ± 24.6 | 50.2 ± 22.0 |
| Distance races per year | 2.8 ± 1.3 | 6.2 ± 1.6 | 6.3 ± 5.4 |
| **Baseline Gait Dynamics** | | | |
| Velocity (m/s) | 2.71 ± 0.41 | 2.97 ± 0.47[a] | 2.96 ± 0.52[a] |
| Stride length (m) | 0.03 ± 0.01 | 0.04 ± 0.01[a] | 0.04 ± 0.01[a] |
| Stride time (s) | 0.74 ± 0.04 | 0.73 ± 0.05[a] | 0.73 ± 0.05[a] |
| Step rate (spm) | 162.3 ± 7.3 | 166.5 ± 11.2[a] | 165.2 ± 9.6[a] |
| Contact time (s) | 0.29 ± 0.04 | 0.27 ± 0.03 | 0.29 ± 0.05 |
| Flight time (s) | 0.45 ± 0.04 | 0.46 ± 0.05[b] | 0.44 ± 0.04 |

spm = steps per minute.
[a] Significant difference from novice group (p < 0.05).
[b] Significant difference from experienced group (p < 0.05).

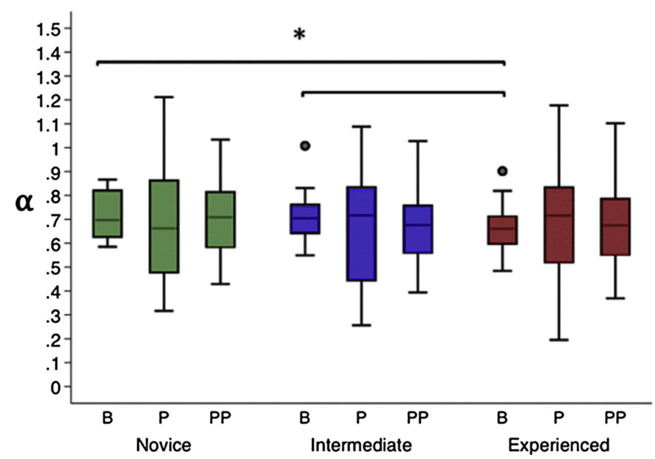


**Fig. 1.** Box plot of step rate α across levels of experience during baseline, perturbation, and post-perturbation. Novice runners have 0–3 years running experience, Intermediate runners have 4–9 years running experience, and experienced have 10 or more years of running experience. B: baseline, P: perturbation, PP: post-perturbation. * indicates significant difference ($P < 0.05$).

### 3.2. Post-perturbation: α values and adaptive response

Step rate α was not significantly different during the post-perturbation period compared to baseline ($ß = -0.14$, $P = 0.38$) or perturbation period ($ß = -0.001$, $P = 0.93$) (Table 3). The level of enforced step frequency was not a significant main effect for post-perturbation step rate α ($ß = -0.038$, $P = 0.16$). Conversely, contact time α was significantly influenced by the level of enforced step frequency ($ß = -0.03$, $P = 0.02$). Enforced step frequencies of 160 bpm

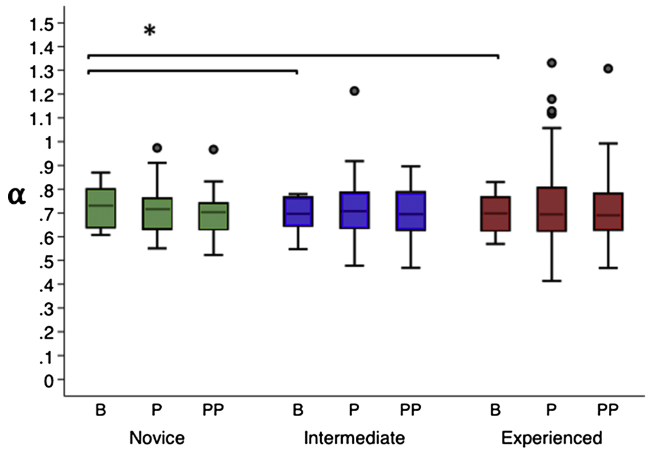


**Fig. 2.** Box plot of contact time α across levels of experience during baseline, perturbation, and post-perturbation. Novice runners have 0–3 years running experience, Intermediate runners have 4–9 years running experience, and experienced have 10 or more years of running experience. B: baseline, P: perturbation, PP: post-perturbation. * indicates significant difference ($P < 0.05$).

($ß = -0.05, ß = -0.11, P = 0.05$), 180 bpm ($P = 0.01$), and 190 bpm ($ß = -0.12, P = 0.03$) were significantly different from 150 bpm but not from baseline ($P = 0.20$–$0.99$). Step rate α was not significantly associated with time to plateau post-perturbation ($r = 0.09$; $P = 0.23$) or time to return to preferred step frequency ($r = 0.10$; $P = 0.19$). Contact time α was not significantly associated with time to plateau post-perturbation ($r = 0.05$, $P = 0.46$) or time to return to preferred step frequency ($r = 0.10$, $P = 0.15$). Adaptive response post-perturbation for each enforced step frequency perturbation level can be found in Table 2.

### 3.3. Running experience influence: α values and adaptive response

Stride-to-stride fluctuations and adaptive responses for the three levels of experience are presented in Table 3. A significant main effect of experience was found for baseline step rate α ($ß = -0.028$, $P < 0.001$, Table 3, Fig. 1). The most experienced runners displayed lower step rate α (i.e., weaker long-range correlations) compared to the novice group ($ß = -0.05$, $P < 0.001$) and the intermediate group ($ß = 0.05$, $P < 0.001$). Experience level was a significant main effect on baseline contact time α ($ß = -0.01$, $P = 0.009$). Baseline contact time α was significantly different between the experienced group and novice runners ($ß = -0.025$, $P = 0.003$) but not the intermediate group ($ß = -0.007$, $P = 0.41$). Additionally, the novice group displayed significantly higher baseline contact time α compared to the intermediate group ($ß = -0.031$, $P = 0.001$).

Experience level was not a significant main effect for relative changes during the perturbation period compared to baseline in step rate α ($ß = -0.035$, $P = 0.08$) or contact time α ($ß = -0.017$, $P = 0.17$). However, the most experienced runners substantially increased step rate α compared to novice runners ($ß = -0.066$, $P = 0.10$) during this period. No significant differences were found for the relative change in step rate α values from baseline to post-perturbation among running experience groups ($ß = -0.012$, $P = 0.35$). Experience level displayed a borderline-significant main effect for the relative change in contact time α between baseline and post-perturbation periods ($ß = -0.019$, $P = 0.06$) with the most experienced group reducing contact time α post-perturbation ($ß = -0.04$, $P = 0.05$) compared to the novice group (Table 3, Fig. 3).

Experience level was not a significant main effect on time to plateau ($ß = -0.057$, $P = 0.31$). Experience level did not influence how quickly runners were able to reach enforced step frequency level ($ß = -6.25$, $P = 0.30$), but the most experienced runners were able to more closely match the enforced step frequency compared to novice

**Table 3**
Stride-to-stride fluctuations (α) and adaptive response for step rate and contact time at baseline, during, and post enforced step frequency compared to baseline values across experience levels.

| | Novice | Intermediate | Experienced |
|---|---|---|---|
| **Baseline** | | | |
| Step rate α | 0.71 ± 0.10 | 0.71 ± 0.12[b] | 0.66 ± 0.11[a] |
| Contact time α | 0.73 ± 0.09 | 0.70 ± 0.07[a] | 0.70 ± 0.08[a] |
| **Perturbation** | | | |
| Step rate α | 0.67 ± 0.22 | 0.67 ± 0.22 | 0.68 ± 0.21 |
| Contact time α | 0.72 ± 0.10 | 0.71 ± 0.12 | 0.73 ± 0.16 |
| Time to plateau (s) | 2.80 ± 0.58 | 2.75 ± 0.72 | 2.69 ± 0.70 |
| Time to reach ESF (s) [c] | 167.7 ± 119.1 | 166.3 ± 119.7 | 152.7 ± 123.0 |
| ESF match (spm) | −6.4 ± 8.3 | −4.7 ± 11.7[b] | −3.7 ± 9.8[a] |
| **Post-Perturbation** | | | |
| Step rate α | 0.70 ± 0.15 | 0.67 ± 0.15 | 0.67 ± 0.17 |
| Contact time α | 0.70 ± 0.09 | 0.70 ± 0.10 | 0.71 ± 0.13 |
| Time to plateau (s) | 2.50 ± 0.90 | 2.56 ± 0.70 | 2.59 ± 0.67 |
| Time to return to PSF (s)[c] | 27.5 ± 98.2 | 17.8 ± 77.4 | 7.78 ± 44.5[a] |
| Step frequency drift (spm) | 1.6 ± 2.5 | 0.7 ± 2.8[a,b] | 1.2 ± 1.8 |

ESF = enforced step frequency, PSF = preferred step frequency, spm = steps per minute.
[a] Significant difference from novice group ($p < 0.05$).
[b] Significant difference from experienced group ($p < 0.05$).
[c] Within ± 2%.

**Table 2**
Stride-to-stride fluctuations (α) and adaptive response during and post-perturbation across enforced step frequency perturbation levels.

| | 150 | 160 | 170 | 180 | 190 | Overall |
|---|---|---|---|---|---|---|
| Difference from PSF (%) | −8.6 ± 5.3 | −2.5 ± 5.7 | 3.6 ± 6.02 | 9.7 ± 6.4 | 15.8 ± 6.7 | |
| **Perturbation** | | | | | | |
| Step rate a | 0.78 ± 0.19[b] | 0.68 ± 0.21[a] | 0.60 ± 0.2[a,b] | 0.65 ± 0.22 | 0.67 ± 0.22 | 0.68 ± 0.22 |
| Contact time a | 0.73 ± 0.13 | 0.73 ± 0.18 | 0.68 ± 0.11 | 0.73 ± 0.12 | 0.73 ± 0.12 | 0.72 ± 0.14 |
| Time to plateau (s) | 2.89 ± 0.71 | 2.79 ± 0.77 | 2.74 ± 0.57 | 2.70 ± 0.66[a] | 2.54 ± 0.63[a] | 2.7 ± 0.68 |
| Time to reach ESF (s) [c] | 107.8 ± 124.3 | 134.3 ± 125.7 | 186.9 ± 111[a] | 167.3 ± 119.4[a] | 207 ± 97.7[a] | 160.6 ± 121.3 |
| ESF match (spm) | 5.2 ± 11.2 | −1.3 ± 7.5[a] | −5.1 ± 7.7[a] | −8.9 ± 4.9[a] | −13.4 ± 6.4[a] | −4.7 ± 10.1 |
| **Post- Perturbation** | | | | | | |
| Step rate a | 0.69 ± 01.5 | 0.69 ± 0.17 | 0.66 ± 0.18 | 0.66 ± 0.17 | 0.69 ± 0.14 | 0.68 ± 0.16 |
| Contact time a | 0.71 ± 0.14 | 0.69 ± 0.09 | 0.73 ± 0.12 | 0.69 ± 0.10 | 0.70 ± 0.11 | 0.70 ± 0.11 |
| Time to plateau (s) | 2.4 ± 0.79 | 2.65 ± 0.77[a] | 2.63 ± 0.66 | 2.65 ± 0.76[a] | 2.42 ± 0.73 | 2.6 ± 0.7 |
| Time to return to PSF (s)[c] | 35.2 ± 111.7 | 2.7 ± 0.83[a] | 24.8 ± 92.4 | 2.9 ± 0.74[a] | 13.9 ± 66.2[a] | 15.9 ± 0.7 |
| Step frequency drift (spm) | 1.9 ± 2.9 | 1.8 ± 1.9 | 1.5 ± 2.2 | 0.54 ± 1.7[a] | 0.12 ± 2.5[a] | 1.2 ± 2.4 |

spm = steps per minute.
[a] Significant difference from novice group ($p < 0.05$).
[b] Significant difference from experienced group ($p < 0.05$).

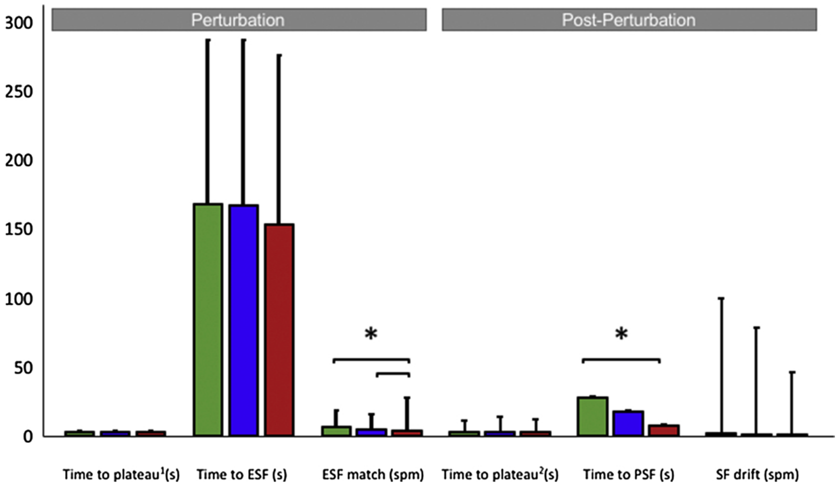


**Fig. 3.** Adaptive response during perturbation and post-perturbation periods. Time to plateau represents the rate at which runners were able to reach a steady state in step frequency. Time to plateau[1] represents adaptation during perturbation. Time to plateau[2] represents de-adaptation post-perturbation. Time to ESF represents the rate at which runners were able to reach ± 2% of enforced step frequency. ESF match represents the difference in steps between enforced step frequency and average step frequency during the perturbation period. Time to PSF represents the rate at which runners were able to reach ± 2% of runner's preferred step frequency. SF drift represents the difference in step frequency between baseline and the post-perturbation period. ESF: enforced step frequency, PSF: preferred step frequency, SF: step frequency.

($ß = 1.77$, $P = 0.005$) and intermediate runners ($ß = -1.25$, $P = 0.04$) (Fig. 4). No differences in matching ability were found between the novice and intermediate groups ($ß = 0.52$, $P = 0.45$). Experience level was a significant main effect on return to preferred step frequency ($ß = -9.89$, $P = 0.007$) but not time to plateau post-perturbation ($ß = 0.045$, $P = 0.24$). The most experienced runners had significantly faster return to preferred times compared to novice ($ß = -19.75$, $P = 0.008$) but not intermediate runners ($ß = 10.06$, $P = 0.16$). No differences were found between novice and intermediate runners ($ß = -9.69$, $P = 0.23$). There was not a significant main effect of experience level on step frequency drift ($ß = 0.11$, $P = 0.36$).

## 4. Discussion

In this study, we investigated the extent to which the strength of long-range correlations (α) changed in response to enforced step frequency perturbations and whether this change was associated with adaptive response. We also explored the influence of running experience on α values and adaptive response. Our results showed that: (1) step rate α and contact time α values were not significantly different during or following a step frequency perturbation, however, the level of perturbation influenced the persistence of stride-to-stride fluctuations, (2) running experience influenced both baseline stability (α) and adaptive response, and (3) there appeared to be less variation in the regulation of contact time compared to step rate.

During the perturbation period, we expected stride-to-stride fluctuations to be lower since previous studies found anti-persistent patterns in stride dynamics when walking with a metronome compared to self-paced walking [21,37–40]. Theoretical predictions of step frequency behavior indicate metronome running would result in less correlated fluctuations [41]. Our results demonstrated that, during the perturbation period, overall step rate α values were not significantly differently from baseline (0.69 ± 0.11 compared to 0.68 ± 0.22, $P = 0.66$). However, an enforced step frequency of 150 bpm appeared to be the most perturbing to runners. This was evidenced by the largest drift away from preferred and longest time to return to preferred step frequency post-perturbation. Previous work [32,33,42] found significant and potentially deleterious biomechanical changes when step frequency was reduced by 10% and potentially positive changes with an increase of 10% from preferred. In our study, the enforced step 150 bpm was, on average, 8.6% ± 5.3% below preferred. That perturbation level also resulted in the highest persistence of step rate α. Taken together, more persistent stride-to-stride fluctuations coupled with higher musculoskeletal tissue loading induced by lower than preferred frequencies and the inability to efficiently return to a preferred state may be a significant contributors to injury susceptibly.

To our knowledge, this is the first study that explored the influence of running experience on global stability and adaptive response. Our results indicated that experience influences the structure of stride-to-stride gait fluctuations and adaptive response. This was evidenced by the baseline step rate and contact time α values, which were significantly different across running experience groups. We found that the most experienced runners were able to match metronome beats most accurately, displayed the largest range of step rates away from their preferred, and were best able to achieve ± 2% of the enforced step frequency. Experienced runners also were most successful at returning to their preferred step frequency. Functionally, this means that more experienced runners may be returning to a preferred state quicker, which reduces muscle activity [43] and, subsequently, accumulated muscle strain or fatigue. These findings may help explain why runners with greater years of experience are less prone to injury [44,45].

Changes in stride-to-stride fluctuation patterns post-perturbation can give insight into how runners restore stability. We found that runners were better able to *de-adapt* than to adapt to perturbations. This is demonstrated by the finding that many runners (64%) were not able to reach ± 2% of enforced step frequency, but almost all runners (97%) were able to return to within ± 2% of preferred step frequency. Step rate α following perturbation was similar to those demonstrated during the perturbation (0.68 ± 0.16 compared to 0.68 ± 0.22, $P = 1.00$). However, contact time α was lower and more similar to baseline during post-perturbation compared to the perturbation period (0.71 ± 0.08 compared to 0.72 ± 0.14, $P = 0.07$). The reason behind this could be that response to a perturbation and de-adaptation post-perturbation represent two critical and separate aspects of functional adaptability. Regulation of step rate indicates the flexibility of the motor system in light of a deliberate goal (i.e., match a specific step frequency), while changes in contact time α may represent a runner's ability to maintain a certain physiologic state or metabolic cost.

Other studies investigating physiologic processes in response to gait perturbations have indicated that runners have a visually driven fast process and a metabolically driven slow process of restoring preferred movement patterns during running perturbations [46–48]. We observed this two-step process in our study; however, our fast process was slightly slower than previous work with running (2.56 ± 0.75–1.47 ± 0.05), and our slow process was slightly faster (15.9 ± 72.1–34.33 ± 0.50). Methodological choices could be causes of the discrepancy among findings. The manipulated step frequencies in the present study were less extreme than previous work and used different criteria to calculate acceptable range for adaptation and de-adaptation.

Longer contact times are thought to be more economical [49]. Post-hoc analysis revealed that mean contact time was reduced during the perturbation period (0.288 ± 0.04 compared to 0.282 ± 0.04, $P < 0.001$) and returned close to baseline levels post-perturbation

(0.287 ± 0.04). This evidence strengthens the assumption that runners prioritize regulation of contact time fluctuations rather than step frequency following a perturbation. Lower contact time α, particularly in the experienced group, indicate that runners are correcting stride-to-stride fluctuations of contact time to improve physiologic state. A greater ability to return to preferred post-perturbation in combination with contact time α behavior confirms that minimization of metabolic cost is a key motivation during running [50], and that experienced runners may be able to *stabilize* their energy expenditure or metabolic cost better than other types of runners. The closer regulation of contact time among all runners was demonstrated in the reduced variation of contact time α between and within subjects compared to step rate α.

A strong motivation for this study was to improve the interpretation of α values. The interpretation of alpha with regard to optimal function is under debate. Some researchers believe that values closer to α = 1 represent ideal adaptability [7,51], while others believe that increased α indicates decreased dynamical degrees of freedom, or lower adaptability [23]. An underlying goal for the present study is to more fully understand the interpretation of α with regard to global stability and adaptability during running. The literature has been somewhat sparse and equivocal when evaluating α with respect to injury. One study found stride parameters in injured runners to be lower [26], while others determined no difference [28]. Fluctuations in footstrike patterns were found to be more persistent in injured runners compared to healthy runners [28]. When examining differences in α between trained and untrained runners, trained runners had lower values across various speeds [52]. Moreover, lower α values were present at preferred running speed with values increasing when speed was farther from this preferred speed, especially when speeds were slower than preferred [29].

Our findings contribute to the growing body of literature, adding a layer of context regarding motor behavior during goal-driven tasks. A significant negative association was found between the time to reach enforced step frequency and α. However, experienced runners displayed the best overall adaptive response and had significantly lower step rate α and contact time α than less experienced runners. Jordan et al. [22] found that higher long-range correlations (persistence) were associated with decreased measures of stability. Our findings may reflect the same trend where runners must de-stabilize or move away from their preferred state to achieve a specific goal (i.e., match the metronome beat). This was also supported by anecdotal information during the test sessions. Runners frequently reported that the enforced 150 bpm was difficult to match and felt *awkward*. Our results supported the claim that lower α values indicate greater global stability and more controlled regulation [53]. However, additional studies are needed to determine whether the underlying cause of lower α values is due to less constrained degrees of freedom [23] and whether increased regulation equates to lower energy expenditure or metabolic cost.

This study has several limitations. Firstly, the sample size in each group was small, which makes it difficult statistically to account for multiple co-variates. Secondly, we used number of years running to determine experience level. Although we found significant differences among groups, there was still large variability within each group. This indicates that there may be another characteristic common to each group that would be a better indicator of proficiency in running skill other than solely number of years running. Using years may not represent who is truly *novice* at running and who is *experienced* or skilled. Finally, we did not randomize the times that the metronome started and ceased. It is possible that runners subconsciously anticipated the change and subsequently altered their motor patterns.

## 5. Conclusion

The present study found that step frequency perturbations less than preferred were sufficient to alter stride-to-stride fluctuations in step rate but not contact time. More persistent step rate α were associated with faster adaptation times across all runners indicating de-stabilization may be necessary to achieve step frequencies away from preferred. However, the most experienced runners (10+ years running) had the lowest α values at baseline and demonstrated the best adaptation and de-adaptation responses. Within groups, there was large variation, and thus, future research should be focused on determining how to best objectify proficiency (skill) in running. Importantly, changes in system stability should be examined in relation to other measures associated with functional adaptability, such as biological variability and complexity, as well as metabolic cost to further elucidate the interpretation of α and its underlying motivations for change.

## Conflict of interest

The authors have no conflict of interest to report.

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