# Quantifying Perturbation Recovery Duration in Response to Belt-Based Perturbations During Treadmill Running – A Functional Data Analysis Approach

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## Summary

This study proposes a functional data analysis approach to determine perturbation recovery duration (PRD) during perturbed treadmill running by tracking whole-body kinematic deviation from unperturbed baseline motion across post-perturbation strides. We demonstrate that the proposed method has excellent sensitivity (97.4%) and specificity (97.3%) in identifying different types of perturbations. Further, PRD shows systematic increase with greater perturbation intensity, indicating high convergent validity as a measure of perturbation recovery. Once confirmed with a larger sample, this method may be used to evaluate the effects of technical or training intervention on PRD and its association with injury rates and performance.

## Introduction

An important aspect of running stability is the ability to recover from large external perturbations [1]. In trail running, where uneven surfaces cause frequent perturbations of varying magnitude, quick and effective post-perturbation recovery with minimal kinematic adjustments (i.e., short PRD) may have important implications for injury prevention and performance optimization [2]. Despite this relevance, there is currently no method of assessing PRD in running, limiting scientific progress in this area.

## Methods

4 recreational runners completed 4 trials of 500 strides at a self-selected running speed (2.88±0.25 m/s) on an instrumented treadmill while 4x3 types of anteroposterior (AP1-AP3; backwards slip) and 2x2 types of mediolateral (ML1, ML2; lateral movement of treadmill body) perturbations were administered in pseudo-randomized order for a total of 16 perturbations per trial. AP1-3 and ML1-2 differed systematically in belt velocity amplitude (AP1: 1.49 m/s, AP2: 2.02 m/s, AP3: 2.54 m/s) and treadmill body displacement (ML1: 0.05 m, ML2: 0.10 m), respectively. Whole-body kinematics were continuously collected using 3D motion capture (Vicon, 100 Hz). Joint angle data were time-normalized to stride-phases based on unilateral initial contacts and divided into an unperturbed baseline data set $Y_{Bi}(t)$ (averaged over strides, excl. 10 strides post-perturbation) and a complete data set $Y_{Sin}(t)$ (all individual strides $n$). Similarity $S(i,n)$ between $Y_{Bi}(t)$ and $Y_{Sin}(t)$ was calculated as:

$$S(i,n) = \frac{\sum_{t=1}^{101} Y_{Bi}(t)\, Y_{Sin}(t)}{\sqrt{\sum_{t=1}^{101}(Y_{Bi}(t))^2}\,\sqrt{\sum_{t=1}^{101}(Y_{Sin}(t))^2}} \qquad (1)$$

and averaged over $i = 1,\ldots,21$ joint angles to produce $S(n)$, a single stride-wise similarity value [–1, 1] (Fig. 1, A) [3]. A participant-specific threshold for classifying perturbed strides was found by maximizing Youden's J statistic [4] and PRD was then defined as the number of consecutive perturbed strides (Fig. 1, B) multiplied by mean stride time. Sensitivity and specificity for stride classification were calculated based on known perturbation events.

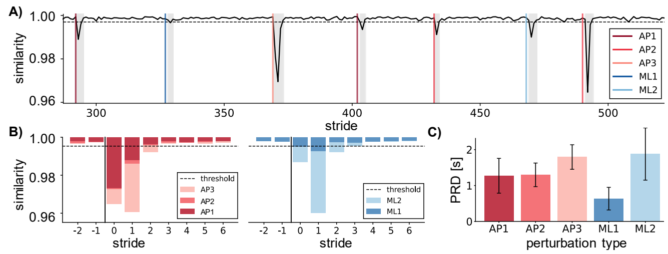


**Figure 1**: *A*: Excerpt of one participant's stride-wise similarity during a perturbation trial. Vertical lines indicate perturbation onset, shaded areas indicate strides classified as perturbed. *B*: Mean similarity of pre- and post-perturbation strides *C*: Mean PRD of different perturbation types. Error bars indicate standard deviation.

## Results and Discussion

Sensitivity and specificity for stride classification were 97.4% and 97.3%, respectively. PRD following AP1, AP2 and AP3 were 1.27±0.49 s, 1.30±0.33 s and 1.79±0.34 s, respectively, while ML1 and ML2 resulted in respective PRD of 0.63±0.31 s and 1.88±0.73 s (mean ± standard deviation; Fig. 1, C). These results demonstrate excellent discrimination between perturbed and unperturbed strides, indicating that imposed perturbations can be effectively differentiated from naturally occurring kinematic variation and that what is captured is likely kinematic deviation necessary to maintain balance. In addition, PRD increases with greater perturbation amplitude and displacement, further supporting the measure's convergent validity [1]. While additional research with larger sample sizes is necessary to determine inter-individual differences and confirm the efficacy of the proposed method, these preliminary results highlight the potential of the proposed method to serve as a tool for quantifying PRD. Eventually, this method may be used to evaluate associations with outcomes of interest (i.e., of performance or injury risk) and technical or training interventions aimed at improving perturbation recovery.

## Conclusions

Our findings demonstrate the utility of quantifying deviation from baseline running kinematics to assess PRD.

## References

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