# Regulating Lateral Stability From Step To Step

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*Abstract* — **We assessed how individuals maintain lateral stability by regulating CoM state fluctuations relative to a novel stability Goal-Equivalent Manifold (GEM). Humans adhere to the proposed stability GEM, exploiting redundancies to coordinate lateral CoM and foot placement dynamics to achieve lateral stability objectives. Observed step-to-step corrections to this stability GEM adapted to different imposed lateral perturbations.**

**Keywords —** ***Stability, Regulation, Goal-Directed Walking***

## I. INTRODUCTION

Maintaining frontal plane stability is a major objective of human walking. Hof's Margin of Stability (MoS), derived from inverted pendulum dynamics [1], is frequently used to quantify average degree of stability. Previous MoS-based analyses fail to address how MoS-relevant fluctuations in CoM state and foot placement are regulated *from step-to-step* to maintain stability.

Here, we developed a new GEM-based framework [2] to define and evaluate one plausible stability objective: maintain a constant mediolateral MoS ($MoS_{ML}{}^{*}$= const.) at each step. We assessed step-to-step fluctuations of lateral CoM state (relative to foot placement). We hypothesized humans would minimize errors relative to a suitable $MoS_{ML}{}^{*}$ GEM as a stabilizing strategy. We quantified how continuous mechanical vs. sensory perturbations altered this step-to-step regulation of lateral stability.

## II. EXPERIMENT

17 older (ages 60+) and 17 young (ages 18-31) adults walked in each of 3 conditions: no perturbations (NOP), and with lateral perturbations of the visual field (VIS) or treadmill platform (PLAT) [3]. We extracted time series of lateral CoM state ($z_n$, $\dot{z}_n$), lateral support boundary as a proxy for lateral foot placement $(u_z)_n$, and minimum mediolateral MoS $(MoS_{ML})_n$ at each step $n$.

## III. STABILITY GEM ADHERENCE

We converted coordinates of adjusted lateral CoM state in the impact Poincaré section [$(z\text{-}u_z)_n$, $(\dot{z}/\omega_0)_n$] into 'goal-*relevant*' ($\delta_P$) and 'goal-*equivalent*' ($\delta_T$) deviations from a linear stability GEM defined by constant $MoS_{ML}{}^{*}$ (Fig. 1A). We quantified variability (std. dev.) and statistical persistence (DFA α; [2,3]) of $\delta_P$ and $\delta_T$ to determine if humans regulate lateral CoM and foot placement fluctuations from step to step consistent with adhering to the $MoS_{ML}{}^{*}$ stability GEM.

## IV. RESULTS & DISCUSSION

All participants demonstrated greatly reduced variability and more-immediate correction of goal-relevant ($\delta_P$) deviations compared to goal-equivalent ($\delta_T$) deviations (Fig. 1B-C). Thus, walking humans adhered to a constant-$MoS_{ML}$ stability GEM, consistent with our hypothesized lateral stability strategy.

Physical forces applied by the moving walking surface (PLAT) substantially altered variability and step-to-step correction of both $\delta_P$ and $\delta_T$. Interestingly, participants also altered stability GEM adherence during VIS, even though these perturbations imposed *no* physical requirement to alter system dynamics.

Thus, step-to-step dynamics of lateral CoM state relative to foot placement are regulated to achieve lateral stability task goals. These regulation strategies were sensitive to both mechanical and sensory perturbations, each of which altered underlying contributions of passive mechanics and/or active control processes relevant to lateral stability in very different ways.

## REFERENCES

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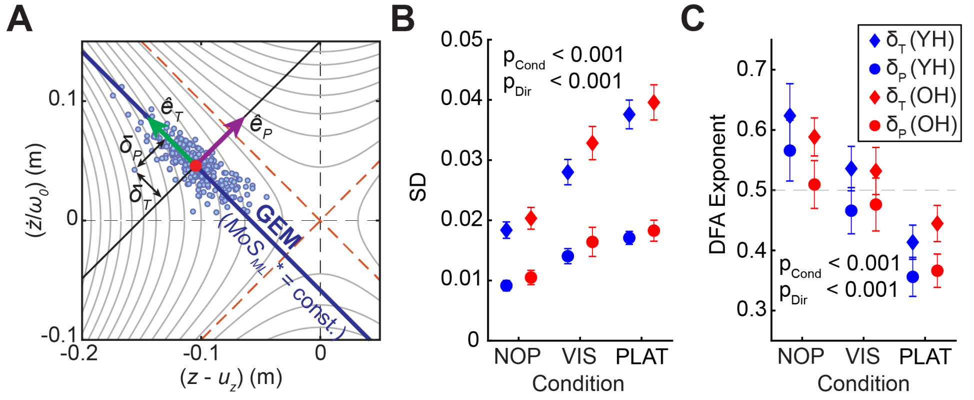

Fig. 1: **(A)** Schematic of the lateral stability GEM for human walking. The solid line defines a MoS-based stability GEM, containing all combinations of adjusted lateral CoM state components ($(z\text{-}u_z)_n$, $\dot{z}/\omega_0)_n$) satisfying the task goal to maintain $MoS_{ML}{}^{*}$ = const. For each trial $MoS_{ML}{}^{*} = \overline{(MoS_{ML})_n}$ . CoM state components were decomposed into deviations tangent $(\delta_T)_n$ and perpendicular $(\delta_P)_n$ to the stability GEM in [$\hat{e}_P$, $\hat{e}_T$]. **(B)** Variability and **(C)** statistical persistence (DFA exponent: α) of $\delta_P$ and $\delta_T$ time series.

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