Applying dynamical systems theory and minimal intervention principle to the control of leg stiffness

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I. Introduction

Experimental data and theoretical models from human and animal studies suggest that effective leg stiffness control during steady-state running has evolved to optimize the competing costs of energy, postural instability and injury risk [1-2]. However, the phase-dependant nature of neuro-mechanical factors that influence effective leg stiffness control are mostly unknown in human running gait. In this study, we examined the effect of habitual foot strike pattern and footwear on leg stiffness control within three task-relevant phases of stance (i.e. touch-down, loading, unloading). The empirical results are interpreted within a quasi-hybrid control framework that blends dynamic systems theory [3] and feedback control [4, 5].

II. Methods

Twenty long-distance runners repeated a 5-minute running test three times, with a different shoe for each trial. Three-dimensional kinematics data were collected at 250 Hz, and time-synchronized with ground reaction force data (1000 Hz). Leg stiffness, k_{leg}, was calculated by the ratio $\Delta F/\Delta L$ (where ΔF is the change in the resultant ground reaction force, while ΔL represents the within-phase change in normalised leg length) for each phase: touch-down (K1, from 0.2-1BW); loading (K2, from 1BW to peak force); and unloading (K3, from peak force to 0.2BW). Control was quantified using stride-to-stride leg stiffness time-series and the coefficient of variability and detrended fluctuation analysis (DFA).

III. Results & Discussion

Results indicate that leg stiffness control is tightly regulated by an active control process during the loading period of stance (Figure 1). In contrast, the touch-down and unloading phases are driven mostly by passive allometric control mechanisms.

The effect of footwear on leg stiffness control was inconclusive due to inconsistent trends across three shoe types. However, stiffness control was affected by landing technique. Habitual rearfoot strike runners have reduced DFA values during the touch-down and unloading phases. These sub-phases are associated with an allometric control process and suggests that rearfoot strike runners express a reduction in system complexity for leg stiffness control and hence, a less adaptable system.

IV. Conclusion

We provided evidence for the dual nature of the interactive hierarchical control systems governing leg stiffness during running, and we present support for higher-level control intervention at loading, while evidence of self-regulatory lower-level control is associated with landing and unloading sub-phases. The likely reason for high-level intervention during loading can be reasoned to emerge from a combination of competing cost factors that cannot be equivalently optimized simultaneously (e.g. energy, stability, and injury avoidance).

References

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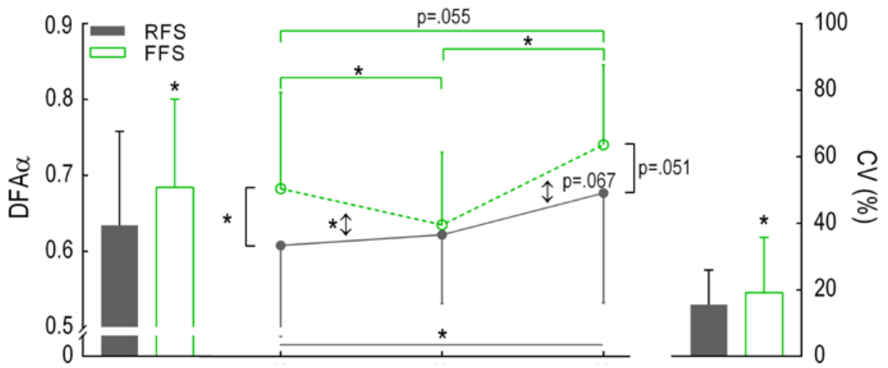

Figure 1. *Group mean and SD of DFAα values averaged across shoe types for each group, and over the three task-relevant sub-phases of the stance phase. Bar graphs show between-group (FFS vs RFS) differences for average DFAα and average CV across sub-phases and shoe type. * represents significance level p < .05; for group × phase interaction effects, and pairwise comparisons for between group and between phase.*