Identifying Templates for Stepping Regulation

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***Abstract* — Biological systems must contend with intrinsic redundancy and noise. Biomechanical *templates* and optimality criteria can define desired mean behaviors. But these systems must also perform tasks with extrinsic task-level redundancy. Here, we describe simple models to define *regulation templates* for how humans adjust stepping movements from each step to the next.**

***Keywords* — Goal-Directed Walking, Variability, Redundancy**

I. Biomechanical Templates For Walking

Biomechanical templates (e.g., Fig 1A), are central to dynamic walking. They are the simplest models (i.e., fewest variables & parameters) of locomotor dynamics that capture the essential behaviors many species exhibit for different gaits [1].

Together with optimality principles, such templates have been widely used to identify average (preferred) gaits (e.g., Fig. 1C) and thus target behaviors for control [1]. While identifying such control targets is key, this alone is not sufficient to describe how people maintain such walking goals across multiple steps.

II. Stochasticity and Task-Level Redundancy

Biological systems are structurally redundant and innately stochastic [1], and walking is always variable [2-3]. However, most *tasks* they perform are also themselves redundant. Indeed, at every step, we have infinite choices of where to step next [4].

Humans rarely walk more than a few consecutive steps [5], in complex environments [2] with fixed and moving obstacles [3] (Fig. 1B). They must therefore adapt at every step, not just on average. Here, we present an analytical framework [6-8] that reconciles issues of optimality, stochasticity, and redundancy.

III. Regulation Templates for Stepping Behavior

We consider any biped (human, robot, model, etc.) walking in a context. We assume some *within*-step process generates each step, but our regulation templates are intentionally agnostic to those details [6,8]. We seek instead to identify how any such within-step processes are adjusted *from step to step* to achieve some particular goal-directed walking task (e.g., as in [2,3]).

We define goal functions to yield empirically-testable hypotheses on task strategies. Equifinality yields all perfect task solutions as a *goal equivalent manifold* or GEM [6] (e.g., Fig. 1D). We define task goals relative to the environment (e.g., "stay in your path"). We model walking dynamics as discrete step-to-step maps with motor and sensory noise [6]. Stochastic optimal control, minimizing task-level error, is used to identify the most parsimonious (i.e., fewest variables & parameters) step-to-step regulation strategies that capture both the sagittal [6-7] and lateral [8] stepping dynamics exhibited by humans.

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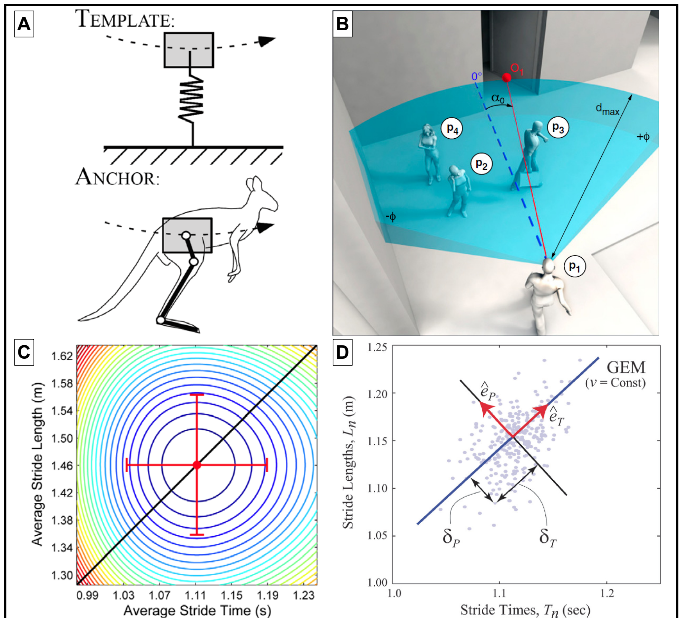

Fig. 1: **A**: Biomechanical Template (from [1]); **B**: Navigating a complex environment (from [5]); **C**: Energetically optimal set point (from [6]); **D**: Stride-to-stride regulation of steps w.r.t. a constant speed GEM (from [7]).

IV. Discussion / Conclusions

Directly analogous to mechanical templates ([1]; Fig. 1A), our *regulation templates* [6-8] act as simplified, empirically-grounded models to describe how the dynamics of a mechanical template should be adjusted at each consecutive step if it is to mimic human behavior. Our regulation templates thus directly compliment mechanical templates: they are the simplest models of the biological perception-action process underlying *goal-directed* walking [3], which is vital to understanding how humans (or any biped) walk in any physical environment [2,5].

Just as mechanical templates can be "anchored" [1] within more elaborate, higher-dimensional mechanical models, our regulation templates can be anchored hierarchically within more elaborate neuro-physiological control models. Thus, these templates both "reveal basic principles" and "yield empirically refutable hypotheses" [1] about step-to-step regulation.

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