nmF: a leg force guided neuromuscular model for balance control in walking

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1 Introduction

Biomechanical models with different levels of complexity are of advantage to understand the underlying principles of legged locomotion. Since detailed modeling of intricate legged systems is challenging, simple conceptual models (i.e, templates) are used for realizing the fundamentals of locomotion at first. Then, by gradually increasing the complexity and details of these models (i.e., anchoring the templates), more elaborate behaviors can be modeled and investigated. In this regard, following a minimalistic approach of gradually increasing model complexity based on *Template & Anchor* concept, in this paper we take a step forward towards addressing the problem of posture control in humans. In doing so, we anchor the Force Modulated Compliant Hip (FMCH [1]) model (Figure 1C) to the neuromuscular level, called nmF (neuromuscular FMCH) model, by replacing hip springs with the Hill type muscle model (Figure 1D). Our control strategy includes leg force feedback to activate hip muscles –originated from the FMCH approach– and a discrete LQR (linear quadratic regulator) for adapting muscle reflexes. We aim to show that by considering muscle mechanics and neural control, FMCH can be translated into the human locomotor system. The main objective in this work is to develop a biologically plausible version of the Virtual Pivot Point (VPP) concept observed in human walking [2]. Here, we show that the nmF model demonstrates human-like walking kinematic and dynamic features such as the Virtual Pendulum (VP) concept. Moreover, the robustness analysis against postural perturbations reveals that the robustness in the nmF model is two times higher compared to the FMCH model and even further higher in the adaptive nmF model.

2 Modeling

The model adopted for simulations is an extension of the Bipedal Trunk Spring Loaded Inverted Pendulum (BTSLIP) model in sagittal plane equipped with hip muscles [1]. In this work, a Rectus Femoris (RF) and a Hamstring (HAM) are added to each leg (see Figure 1D). For modeling these muscle pairs for each leg, we use the contractile element part of the Hill-type muscle model in [3]. The BTSLIP model and muscle model parameters are taken from [4].

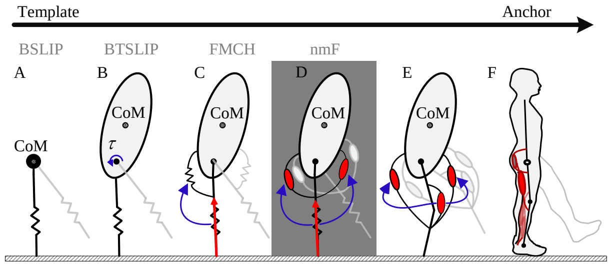


Figure 1: Model evolution from template to anchor; the nmF model investigated in this paper is highlighted.

3 Control Approaches

The control strategy adopted here for the neuromuscular BTSLIP model consists of the swing and balance subfunctions. In the swing phase, a robust strategy for controlling the leg angle, named VBLA (Velocity Based Leg Adjustment) is employed [5]. In VBLA, a weighted average of the Center of Mass (CoM) velocity vector $\vec{V}$ and the gravity vector $\vec{G}$ yield the leg direction $\vec{O}$ as:

$$\vec{O} = (1-\mu)\vec{V} + \mu\vec{G} \tag{1}$$

with weighting constant μ ranging from 0 to 1.
As for the balance control, we use an extension of FMCH to the neuromuscular level, in which the leg force F_s is employed as a sensory pathway for activating HAM and RF muscles. For that, the sensory signal (F_s) is delayed (ΔP), gained (G) and then passed through the excitation-contraction coupling to create the muscle activation (A); see Figure 2. This neural feedback can be formulated as follows:

$$\begin{aligned} STIM(t) &= STIM0 + GF_s(t-\Delta P) \\ T\frac{\partial A}{\partial t} &= Sat(STIM(t)) - A(t) \end{aligned} \tag{2}$$

where in the first line, $STIM$ and $STIM0$ are defined as the stimulation signal and the stimulation bias, respectively. In the second line, the Sat function is for saturating the stimulation to a predefined range and a first-order differential equation relating stimulation to activation signal is described with T being a time constant. Furthermore, to increase the robustness of the model, a discrete LQR is designed using the system states to adapt the reflex gains once per step.

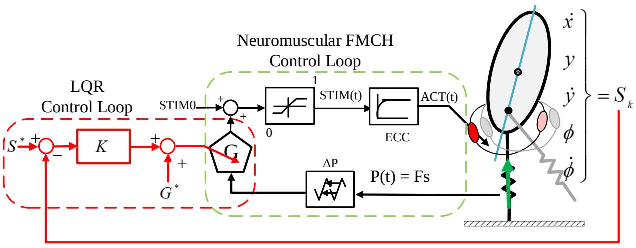


Figure 2: Control loop schematic: In the inner loop, the stance leg force is used as the feedback for creating muscle activations. And in the outer loop, a discrete LQR is implemented to tune the reflex gains once per step at mid-stance.

4 Results and Discussion

Robustness against perturbations among different methods is compared in Figure 3. For comparison, the Basin of Attraction (BoA)—identified by a range of initial trunk angles (ϕ) and velocities ($\dot{\phi}$) in which a model can predict stable walking—is used. It reveals that the size of BoA in the nmF is roughly twice that of the FMCH. It also shows that the adaptive nmF model has the largest BoA as expected. These results show that our bioinspired nmF model is considerably less sensitive to the initial conditions (or perturbations) compared to the biomechanical models (e.g., FMCH). From the neuro-mechanical point of view, our proposed neuromuscular model predicts the emergence of the VPP; see Figure 4. The existence of an emerging intersection point in the nmF model shows that the addition of muscle does not result in deviating from the previous FMCH balance control concept. Moreover, it supports that human muscles are able to control the upper body in a way that the virtual pendulum concept holds in a more human like way (higher VPP positions similar to those of human walking).

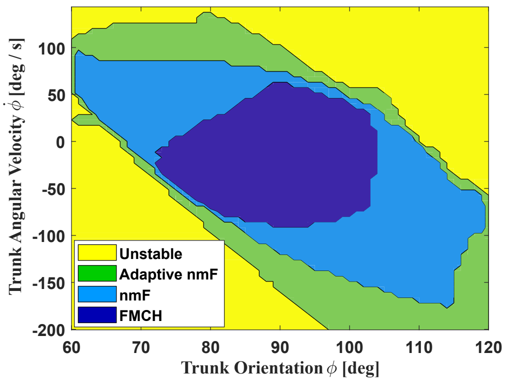
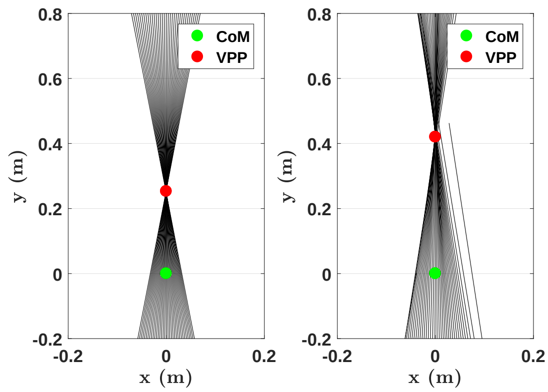


Figure 3: BoA for FMCH, nmF and adaptive nmF models.

5 Conclusions

In this study, balance control in a neuromuscular SLIP–based model which represents a template for human walking is achieved through activating hip muscles proportional to the leg force feedback. We showed that this positive feedback of leg force as muscle activation is sufficient for ensuring a stable walking gait and supports the VP concept. Moreover, the model predicts to increase the range of tolerable disturbances and convergence speed to steady state walking motion after perturbation.

Both BTSLIP and FMCH are mechanical conceptual models which fail to describe the neuromuscular structure of the human body. In order to validate the value of the predictions made by these models, we need to test them in a human-like body structure. The nmF model is an attempt to overcome this limitation by representing a pair of thigh muscles and its neural control. In our study, the primary outcome is not to show any advantages of the nmF compared to the other conceptual models. Instead, we prove that the concepts hold for a more human-like structure of the model. With the nmF, we can now investigate in more detail, which structural and functional conditions (e.g., muscle properties and arrangements) are required for a given motor task (e.g., walking).



(a) FMCH **(b)** nmF

Figure 4: Ground reaction forces plotted w.r.t. trunk coordinate system centered at CoM for FMCH and nmF models.

6 Acknowledgment

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