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Simple Standing Control using Hip and Ankle Strategies

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Abstract

Standing stability is a major concept with broad industrial relevance, especially in lower-limb rehabilitation and the assessment of neurological impairments. This project develops a biomechanical model of human quiet standing that uses both ankle and hip strategies to understand how the ankle muscles contribute to postural control. Hill-type muscle models of the Soleus and Tibialis Anterior are implemented to represent the ankle muscles connecting the foot and shank, and their simulated activations are compared against experimental EMG data to assess the physiological plausibility of the model. Trunk posture is stabilised using a PD controller, while the hip strategy is first implemented through a flywheel-like arm and subsequently refined using PD control of the arm to stabilise the body.

Keywords: Standing Stability, Ankle Strategy, Hip Strategy, Hill-type muscles

1. Introduction

Standing balance is a basic motor skill that is a necessity for safe mobility, independent living, and most industrial and everyday tasks. Loss of control with posture defines both aging and many neurological disorders, and balance dysfunction is strongly associated with an elevated risk of falls, reduced quality of life, and increased healthcare utilization [1, 2]. To grasp and hopefully improve balance function in the future, the physiology of upright human posture is frequently idealized using an inverted pendulum model, in which the central nervous system controls the movement of the center of mass on a small base of support using muscular and joint moment actions [3, 10]. Traditional research has differentiated two main balance control patterns in the sagittal plane, namely the ankle and hip strategies, which are marked by different joint kinematics, muscular synergies, and ground reaction force profiles. In contrast to the ankle strategy, where a whole-body single-segment inverted pendulum model describes human posture with control actions confined to ankle muscles, in the hip strategy, balance control involves a multi-segment, larger, and faster motion at the hip joint, especially in response to more challenging balance support situations [4].

In quiet stance and small disturbance reactions, ankle strategy is predominantly used, with a primary role played by ankle muscles such as Soleus and Tibialis Anterior in controlling sway and in the production of sway-preventing torque [5]. EMG analysis indicated a strong time lock of Soleus activity to forward sway with resulting plantarflexion torque, which corresponds to a restoring torque, in contrast to which Tibialis Anterior activity can be weak or provide important proprioceptive input, especially concerning modifications of sway and ankle joint configuration [6, 7]. A different pattern of ankle and hip strategies with delayed onset and reduced EMG amplitude can be noted in more challenging balance reactions and in patients with chronic ankle instability and neurological deficits, which can be a challenge to dynamic balance control capabilities[8, 9].

Muscle-level modeling of posture control is most often carried out with Hill models of muscle-tendons, which include a contractile element in series and parallel with elastic elements to simulate force-velocity-length relationships. Hill models have seen widespread application in studies of control strategies in locomotion and posture. In studies of balance control during upright stance, Hill models of major ankle muscles, such as Soleus and Tibialis Anterior, can be used to enable a direct comparison of model-generated patterns of muscle activation with measured EMG, thus assessing the physiological validity of hypothesized control strategies [7]. A muscle-level perspective can be especially important in rehabilitation contexts where therapy focuses on stimulation of particular muscle groups, but can also have application in exoskeleton devices in which control is exercised through interaction with human muscles [11].

Recently, ankle and hip control strategies have been incorporated in more integrated control models through modeling studies that have shown mixed control strategies can arise with fairly simple control architectures and are strongly influenced by control strategy selection based on task, perturbation type, and biomechanical imperatives. In addition, hybrid and intermittent control models in which passive stiffness and short-term active control in a fixed pattern at both ankle and hip joints have allowed important characteristics of experimental sway trajectories to be reproduced and have shed light on how tradeoffs in stability, cost, and robustness can be achieved through control by the nervous system [1]. More basic research in robotics and control of humanoids has explored incorporating arm and trunk movements via control algorithms based on using these upper body segments in effect as a form of mass reversal strategy in balance recovery by replicating a hip strategy when ankle torques alone are insufficient to balance a disturbance [12].

Based on these existing studies, this project aims to augment a neuro mechanical model of human standing based on Hill-type muscle models of both Soleus and Tibialis Anterior muscles with a joint-level control strategy of the trunk and an upper limb mechanism based on a hip strategy model. The model will be used to determine the response of the ankle to different externally applied perturbations, and see the how to ankle muscles react to provide torque. Trunk tilt will be controlled via a PD control strategy to simulate upright-standing posture regulation, and an upper limb model will first be described using a flywheel model for balance restoration purposes with hip-like torques, later being controlled using a PD control strategy to simulate a more physiological hip strategy based on balance control. Through discussions, we will try to understand the closeness of the model's control strategy to the human standing control strategy. For simulation purposes, the Simulink Multi-body module provided by Simulink was utilized to create skeletal models, and MATLAB was used for analysis of joint torque and position data. The following are necessary assumptions that are stated for the sake of discussion and creation of the model.

1. Only two muscle models are used in the simulation. They are the Soleus muscle and the Tibialis Anterior Muscle. Both are responsible for connecting the foot to the shank of the leg and performing DorsiFlexion and Plantarflexion, respectively.
2. The moment arms for the above-mentioned muscles are taken to be constants. Due to the small deflection angles of the ankle joint, this can be taken to be more or less precise.
3. The lengths of the muscles are modeled as a simple cosine function of the ankle joint angle. The equation for which is given by Eq. (3).

Table 1. Dimensions of body parts

body part	length (m)	width (m)	height (m)	density (gcm^{-3})
foot	0.2	0.1	0.04	1.10
heel	0.05	0.1	0.04	1.10
leg	1.0	0.1	0.04	2.06
trunk	0.6	0.34	0.08	2.50
arm	0.8	0.1	0.08	0.85

Table 2. Dimensions and limits of joints

specifications	ankle joint	hip joint	shoulder joint
length (m)	0.1	0.1	0.1
radius (m)	0.02	0.02	0.02
density (gcm^{-3})	1.10	2.06	0.85
lower lim (deg)	45	-30	-
upper lim (deg)	120	120	-
Torque limits (Nm)	(-107, 27)	(-500, 500)	(-50, 50)

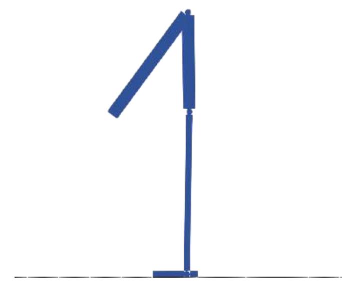


Figure 1. A Sample image of the model in Simscape

2. Musculoskeletal Model

We shall first discuss the setting up of the model in the Model Setup section. Further, the muscle models and control systems are explained in the Method section.

2.1 Model Setup

The skeletal model created in Simulink consists of a foot, an ankle joint, a heel, a leg (shank and thigh combined), a hip joint, a trunk, a shoulder joint, and an arm. The body parts are all taken as cuboids, and the joints as cylinders. The necessary specifications of corresponding body parts and joints are given in Table (1) and Table (2), respectively. An infinite plane is created, and ground mechanics are simulated using the spatial contact force block. The model can be vaguely compared to a 4R- planar serial manipulator, where the links are the body parts, and the joints are the manipulator joints incorporating a rotational degree of freedom. A sample depiction is shown in Fig. (1).

2.2 Method

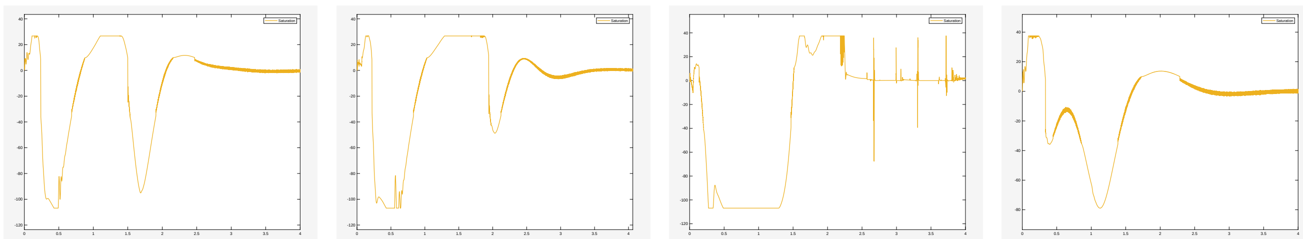
We shall discuss the modeling of the ankle control method for the ankle strategy, the upright position of the trunk using the hip joint, and then the hip strategy using the arm as a flywheel.

2.2.1 Ankle Control

As discussed earlier, the ankle is controlled by the Soleus and the Tibialis Anterior muscles. The current ankle joint positions and velocities are obtained, and passed through a PD control to obtain a torque reference as given in Eq. (1).

$$\tau^a_{ref} = k^a_p(\theta^a_{des} - \theta^a) - k^a_d\dot{\theta}^a \tag{1}$$

The values of k^a_p and k^a_d are determined first solely through an ankle strategy experiment. Based on the reference torque value, depending upon its sign, the command is passed to the corresponding muscle model. A positive τ^a_{ref} indicates activation of the tibialis anterior muscle, and a negative τ^a_{ref} indicates activation of the soleus muscle. The activation of the



(a) Net Ankle Torque for 40N push **(b)** Net Ankle Torque for 70N push **(c)** Net Ankle Torque for 120N push **(d)** Net Ankle Torque for 30N pull

Figure 2. Net Ankle Torque for for different push values

muscles is realized w.r.t the corresponding ankle joint torque limits. These limits are used to normalize the reference torque τ^a_{ref}, becoming an activation a given in Eq. (2).

$$a = \begin{cases} \frac{-\tau^a_{ref}}{107}, \tau^a_{ref} < 0 \\ \frac{\tau^a_{ref}}{27}, \tau^a_{ref} > 0 \end{cases} \tag{2}$$

The hill-type muscle models used in this model are referred to H. Geyer's work from the course "Biomechanics and Motor Control", taught at Carnegie Mellon University. The muscle model requires mainly two inputs: the muscle length and the corresponding activation, and gives the muscle force as the corresponding output. The muscle length can be modeled by Eq. (3).

$$l_m = (l_{opt} + l_{slack}) + k\cos(\theta^a) \tag{3}$$

Where the constant k is muscle-dependent, but for our cases, it has been taken as a third of the sum of optimum muscle length and tendon slack length. The corresponding force output is then multiplied with their corresponding moment arms r_{ta} and r_{so}. The corresponding net torque is obtained as given by Eq. (4):

$$\tau^a_{net} = \tau_{ta} - \tau_{sol} \tag{4}$$

$$\tau^a_{net} = F_{ta}r_{ta} - F_{sol}r_{sol} \tag{5}$$

2.2.2 *Hip control*

The objective of the hip control is to maintain an upright trunk position. This is modelled using simple PD control, using Eq. (6) as given below.

$$\tau^h = k^h_p((\theta^a_{des} + \theta^h_{des}) - (\theta^h + \theta^a)) - k^h_d(\dot{\theta}^h + \dot{\theta}^a) \tag{6}$$

Where k^h_p and k^h_d are experimentally determined values.

2.2.3 *Arm control*

The arm is modeled as a flywheel to try to balance out the angular momentum generated as a result of a disturbance. The flywheel control method utilized is the Bang-Bang control method [13]. The control algorithm gives the following shoulder torque equation.

$$\tau^s_{fly}(t) = \tau^s_{\max} + 2\tau^s_{\max}u(t - T_1) - \tau^s_{\max}u(t - T_2) \tag{7}$$

Where $u(t)$ is the step function, and the constants T_1 and T_2 are determined through experiments; however, through certain derivations from [13], a constraint $2T_1 = T_2$ is applied. After time $t = 3T_1$, the flywheel torque is set to zero. However, at a certain time (chosen $t = 5T_1$), PD control is reapplied onto the shoulder joint using Eq. (8).

$$\tau^s = k^s_p((\theta^a_{des} + \theta^h_{des} + \theta^s_{des}) - (\theta^h + \theta^a + \theta^s)) - k^s_d(\dot{\theta}^s + \dot{\theta}^h + \dot{\theta}^a) \tag{8}$$

3. Simulation and Results

The model was subject to a push force on the middle of the torso, in the horizontal direction. Forces of magnitude 30N, 40N, 70N, and 120N, on the sagittal plane. The experiments were performed for 5 seconds each, but stopped earlier if the model stabilized earlier. The external force is initially applied for 0.1 seconds. The net ankle torques for each case are recorded and plotted as shown in Fig. (2).

Clearly, from Fig. (2), for cases 30N, 40N and 70N, the system remained stable, however, for a much larger value, the ankle and hip strategy together can't counter a larger force based on the constraints set. This is because as the model first uses the hip strategy to counter most of the push force, the corresponding limit on the maximum shoulder torque limits its ability to counter larger forces. Hence, a larger portion of the remaining momentum has to be taken care of by the ankle strategy.

For the pull force, despite the external force applied in the opposite direction, the rate of convergence remains more or less the same, however, the role of the tibialis anterior seems to have been compensated more or less by the hip strategy. This could be a reason for the similarity in plots Fig. (2a) and Fig. (2d) due the dominance of hip strategy in both cases.

4. Discussion

It is clear that the neuromuscular model articulates the potential for combining physiological muscle models with robot-control approaches on a human standing stability platform. Simulation outputs for the ankle pattern indicate that the Hill muscle model Soleus portrays vigorous and phase-locked contraction patterns that depend on the velocity of forward sway, delivering a resulting torque that opposes the force of gravity. This reflects closely the experimental results provided by the electromyographic (EMG) work shown in [3], indicating the Soleus muscle to act as the chief supporting muscle during quiet standing, and the work in [14], employing center-of-pressure (CoP) velocity that highly correlated with the time-dependent activation of the Soleus muscle. Conversely, the simulation outputs on the TA muscle pattern presented particular patterns reflecting low-intensity bursting that mainly acted on the recovery phase associated with backward sway. This variant reflects a divergence regarding certain data gathered by [15] on certain older adults indicating higher levels of TA-Soleus co-contraction (stiffness force) among more unstable human populations.

For larger disturbances (>80 N), there was a successful transition to a hip strategy with the flywheel-arm system. The effectiveness of this "mass reversal" strategy in increasing the basin of stability is consistent with the robotic control schemes proposed by [12], which experimentally confirmed that sole torque in the ankle is not sufficient to trigger a recovery below similar force thresholds (70-80 N). Although our system succeeded in stabilizing effectively, the hip/trunk reaction torques caused a short period of transient oscillations, which converged quicker than in hip strategies witnessed in biological movements. [16] explains that in biological hip strategies, there is a complex coordination of multi-body movements, as well as a control of damping, in a process of reducing muscle metabolism, indicating a future development of our model should attempt to include terms of optimal control, opposed to solely error-oriented terms in a PD controller, in a similar bio-reflective process witnessed in human experiments.

References

[1] Morasso, Pietro. "Integrating ankle and hip strategies for the stabilization of upright standing: An intermittent control model." Frontiers in computational neuroscience vol. 16 956932. 17 Nov. 2022, doi:10.3389/fncom.2022.956932

[2] "Postural Control." Physiopedia,. 5 May 2022, 21:01 UTC. <https://www.physio-pedia.com/index.php?title=Postural_Control&oldid=304147>.

[3] Winter, David A.. "Human balance and posture control during standing and walking." Gait & Posture 3 (1995): 193-214.

[4] Runge, C F et al. "Ankle and hip postural strategies defined by joint torques." Gait & posture vol. 10,2 (1999): 161-70. doi:10.1016/s0966-6362(99)00032-6

[5] Gatev, P et al. "Feedforward ankle strategy of balance during quiet stance in adults." The Journal of physiology vol. 514 (Pt 3),Pt 3 (1999): 915-28. doi:10.1111/j.1469-7793.1999.915ad.x

[6] Choi, Suwoong, et al. "Muscle Activation of Soleus and Tibialis Anterior according to Landing Strategy of Initial Contact during Descending Stairs: Comparison of Forefoot and Whole Foot." Physical Therapy Rehabilitation Science 10.1 (2021): 16-21.

[7] Jaber, Hatem, et al. "Neuromuscular control of ankle and hip during performance of the star excursion balance test in subjects with and without chronic ankle instability." PloS one 13.8 (2018): e0201479.

[8] Day, James T., Glen A. Lichtwark, and Andrew G. Cresswell. "Tibialis anterior muscle fascicle dynamics adequately represent postural sway during standing balance." Journal of applied physiology 115.12 (2013): 1742-1750.

[9] Versteeg, Chris S., Lena H. Ting, and Jessica L. Allen. "Hip and ankle responses for reactive balance emerge from varying priorities to reduce effort and kinematic excursion: A simulation study." Journal of biomechanics 49.14 (2016): 3230-3237.

[10] Yang, Lizhi, et al. "Bracing for Impact: Robust Humanoid Push Recovery and Locomotion with Reduced Order Models." arXiv preprint arXiv:2505.11495 (2025).

[11] Chua, Matthew C., et al. "Movement strategies for maintaining standing balance during arm tracking in people with multiple sclerosis." Journal of neurophysiology 112.7 (2014): 1656-1666.

[12] Shen, Keli et al. "Reproducing Human Arm Strategy and Its Contribution to Balance Recovery Through Model Predictive Control." Frontiers in neurorobotics vol. 15 679570. 17 May. 2021, doi:10.3389/fnbot.2021.679570

[13] Stephens, Benjamin. "Humanoid push recovery." 2007 7th IEEE-RAS International Conference on Humanoid Robots. IEEE, 2007.

[14] Fok, Kai Lon, et al. "Co-contraction of ankle muscle activity during quiet standing in individuals with incomplete spinal cord injury is associated with postural instability." Scientific Reports 11.1 (2021): 19599.

[15] Vette, Albert H et al. "Ankle muscle co-contractions during quiet standing are associated with decreased postural steadiness in the elderly." Gait & posture vol. 55 (2017): 31-36. doi:10.1016/j.gaitpost.2017.03.032

[16] Afschrift, Maarten, et al. "Mechanical effort predicts the selection of ankle over hip strategies in nonstepping postural responses." Journal of Neurophysiology 116.4 (2016): 1937-1945.