# A neuromuscular model of human balance control that combines flexibility and stability

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## I. INTRODUCTION

Balance control in human walking is a complex task that involves the interplay between skeletal biomechanics, muscle neurophysiology, reflex pathways and descending motor commands. Various sensory systems estimate the state of the body in space and initiate adaptations of the movement plan to unexpected disturbances preventing the body from falling. This requires both stability to maintain upright posture during walking and flexibility to allow adaptations of the movement plan needed to compensate unexpected disturbances such as stumbling. Changes of the movement plan must then be realized by motor command adjustments that are integrated with biomechanics, muscles and reflex pathways of the spinal cord. Even though many studies show the importance of balance control in human locomotion, relatively little is known about the concrete neural implementation of these mechanisms [1] [2]. Our goal is to build a neurally plausible model of human locomotion. The system is constrained by established dynamics of the spinal reflex pathways, muscle physiology and biomechanics, and must be able to generate movement plans for variable task goals and update movements in real-time based on sensory information.

## II. MODEL & RESULTS

We present a 3D-neuromuscular model of human locomotion. Our work is based on an established neuromuscular model for walking [3], [4] controlled by spinal reflexes and a simple supraspinal control layer. It is able to reproduce human walking gaits, predicts muscle activation patterns and can adapt to changing environments when parameters are changed. However, the model lacks the flexibility to perform voluntary movements or change movement direction or speed, or combine steady-state locomotion with additional tasks.

Our neuromuscular model accounts for the need of flexibility and stability during walking. To achieve flexibility, we replace the explicit reflex loops with a generic stretch reflex for each muscle. The system generates movement plans as dynamical systems in task space, then achieves these movements by shifting the activation threshold of the stretch reflex to generate muscle forces according to the movement plan. The biomechanical model comprises eight degrees of freedom, realistic moment arms and 22 Hill-type muscles [3]. Muscles are innervated by $\alpha$-motorneurons and are controlled by threshold shifts of the stretch reflexes [5].

Movement plans are organized on the task level. Vestibular feedback is used to determine a state dependent target foot placement position for each step that generates stable walking [6]. A movement plan towards that target foot placement position is generated by a damped harmonic oscillator. Oscillator parameters are dynamically updated by a neural network that accounts for balance related changes in the target foot placement position and for perturbations of the body in space.

Our model is able to robustly implement goal-directed steps in a physics-based environment. It compensates for disturbances and is flexible enough to cover large portions of the workspace. During locomotion, it estimates target foot placement positions and generates steps towards that target position reliably incorporating updates of the movement plan. Resulting foot trajectories conform to experimental data.

## III. CONCLUSION

Our 3D-neuromuscular model of human locomotion is able to generate and realize update-able movement plans to different portions of the workspace. It accounts for biomechanics, muscle dynamics, reflexes and interactions with the ground and generates locomotion in a physics based environment.

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