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**A spinal reflex based neuromuscular model of human locomotion investigated against unexpected disturbances**

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**Abstract:**
The control mechanism of the human spinal cord in generating muscle activations for locomotion has been studied over decades. One of the main hypotheses is that central pattern generators (CPGs) produce the background activations, and spinal reflexes produce compensatory activations against disturbances. However, the contribution of CPGs in human locomotion has not been verified. To this end, we investigate this hypothesis using a previously proposed CPG-free, proprioceptive-reflex-based neuromuscular simulation model. It has been demonstrated in physics simulation that the model generates human-like kinematics, dynamics and muscle activations. Furthermore, the same control with different control parameters generates various locomotion behaviors, such as running, negotiating slopes and stairs, and changing walking directions. Here, we examine the reflex based model with a range of unexpected disturbances to test the necessity of CPGs in explaining the responses of humans during walking. Five disturbance experiments from the literature, which encompass most artificial (epidural stimulation, tendon tap, and local joint stretches) and natural disturbances (trip and slip) used in human gait experiments, are replicated in simulation with the reflex based neuromuscular model, and its responses (immediate changes in muscle activations) are compared with those reported from the human experiments. The response trends over the gait cycle and disturbance intensities of the model matches well with those of humans against all disturbances; excluding the noticeably defective responses, which also can be improved within the proprioceptive reflex based control structure, about 80% of the properly scaled model responses fall within 1 standard deviation of human responses. However, a fundamental change in the control structure seems

necessary to explain the response amplitudes of humans; the response amplitudes of the model are similar to those of humans only for artificial disturbances and are much smaller for natural types of disturbances. Adding cutaneous reflex pathways to amplify the activities of the proprioceptive reflexes of the model may explain the large human responses against natural types of disturbances. Interestingly, the current study suggests to include more reflexes to the CPG-free reflex based model, leaving obscure the functionality and necessity of CPGs in human locomotion.

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