

# Modeling and Simulation of Balance Recovery Responses to Tripping

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## INTRODUCTION

Falls induced by tripping are harmful for older adults, and cause severe injury, hospitalization, and disability. Appropriate postural response strategies are necessary to avoid these accidents [1, 2, 3, 4]. Thus, experimental gait studies have been key in describing these responses. However, the causes of failed recovery attempts are difficult to determine from experiments alone. Computational modeling and simulation techniques can complement experimental approaches to gain a greater understanding of trip-initiated postural responses and causes of falls. The current work presented here describes our preliminary efforts to model balance recovery strategies triggered by tripping using physical simulation to understand the effects of specific parameters of the postural response on the dynamics of the response.

## METHODS

### *Capturing Balance Recovery Responses to Tripping*

Nine young (21-35 year old) and six older (65-75 years old) healthy adults, screened for neurological and musculoskeletal abnormalities, were recruited for participation in this study. First, range of motion test was recorded to construct the kinematic structure of each subject and to convert marker position data to joint angle data with Vicon iQ. Next, subjects were asked to walk onto a known dry floor to retrieve baseline gait characteristics. Subjects were then informed that in the next set of trials, at some point they would experience a trip. Subjects had no knowledge of the exact timing at which it would occur. Three trips were randomly inserted into 5 unperturbed trials. All subjects were harnessed to prevent hitting the floor in the event of an irrecoverable loss of balance. Whole body motion data were collected at 120 Hz. The trips were triggered at heel contact of the leading/right foot to catch the trailing/left foot in mid-swing. Only the first (unexpected trip) is used for further analysis.

### *Simulating Responses to Tripping*

To model the dynamics of tripping responses, which

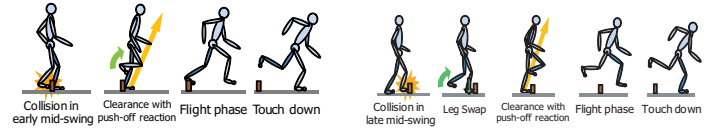


Figure 1. Tripping strategies. Left: elevating strategy, and right: lowering strategy.

were categorized as elevating or lowering strategies [1], physical controllers were designed with finite state machines (FSM) to determine the desired position and gains of each controlled joint for each state using proportional derivative (PD) controller:

$$\tau = k_p(\theta_d - \theta) - k_d\dot{\theta},$$

where  $\theta_d$  is desired joint position,  $\theta$  and  $\dot{\theta}$  are the current joint angle and angular velocity, and  $k_p$  and  $k_d$  are spring and damper gains, respectively. The parameters were set for each state in FSM. The simulation was initialized just before the trip occurred using the joint angles and velocities recorded experimentally. Tripping was simulated in 2D (sagittal plane), and all the parameters were manually set so that resulting motions were as close to motion capture data as possible. The posture of the upper body was maintained to be that recorded at the onset of the trip with high gains. Tripping/collision forces were modeled using the data published by Pijnappels et al. [3].

The controller for an elevating strategy had four states: *Passive Reaction*, *Clearance*, *Flight Phase*, and *Touch Down* (top of Figure 1). In *Passive Reaction*, the support leg maintained the torso attitude, and the swing leg was moving forward to prepare for stance. Tripping forces were applied to the swing toe. The durations of the passive reaction reported in [2] were used to change the state to *Clearance*. In *Clearance*, flexion torques were applied to the swing leg to clear the obstacle, while extension torques were applied to the support leg to perform a push-off reaction. The compensation torque was also applied to the support ankle to achieve *Flight Phase*. When the support leg left the ground, the state became *Flight Phase*. In

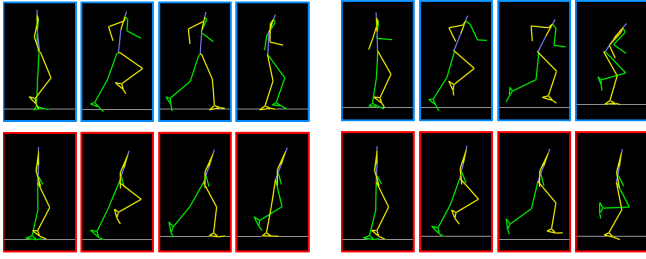


Figure 2. Results of simulating the elevating strategy with Double Support (left) and Flight Phase (right). Top: motion capture data and bottom: simulated motion. Yellow and green legs were tripped and non-tripped legs, respectively.

Flight Phase, extension torques were applied to the front leg for ground contact, and flexion torques were applied to the rear knee. In Touch Down, torques to maintain the torso attitude were applied to the joints of the support leg, and flexion torques were applied to the swing leg to move forward.

The controller for a lowering strategy had five states: *Passive Reaction*, *Leg Swap*, *Clearance*, *Flight Phase*, and *Touch Down* (bottom of Figure 1). *Passive Reaction* in the lowering strategy was the same as that in the elevating strategy. In *Leg Swap*, extension torques were applied to the swing leg for ground contact, and the support leg kept the stance posture. Once the swing leg touched the ground, the state became *Clearance*. In *Clearance*, flexion torques were applied to the non-tripped leg to become a swing leg and to clear the obstacle. The tripped leg became a support leg, and extension torques were applied for a push-off reaction. *Flight Phase* and *Touch Down* were the same as those in the controller of the elevating strategy.

## RESULTS AND DISCUSSION

Out of 15 subjects total, seven performed an elevating strategy and eight performed a lowering strategy. In addition to the flight phase described by Pijnappels et al. [3], we observed some subject recovery strategies to include a double support phase. This double support phase was observed when walking speed was slow ( $\sim 1.0$  m/s). Eight subjects (four performing elevating strategy, four performing lowering strategy) exhibited this double support phase. Since the double support phase was observed in several subject recovery strategies during slow speed walking, Double Support was used in these simulations instead of Flight Phase if walking speed was slow or if flight phase could not be achieved. When both legs touched the ground, the state became Double Support, and flexion torques were applied to the rear leg for the step.

The simulation results for both the elevating and low-

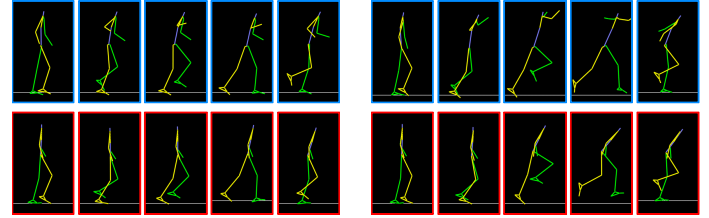


Figure 3. Results of simulating the lowering strategy with Double Support (left) and Flight Phase (right). Top: motion capture data and bottom: simulated motion. Yellow and green legs were tripped and non-tripped legs, respectively.

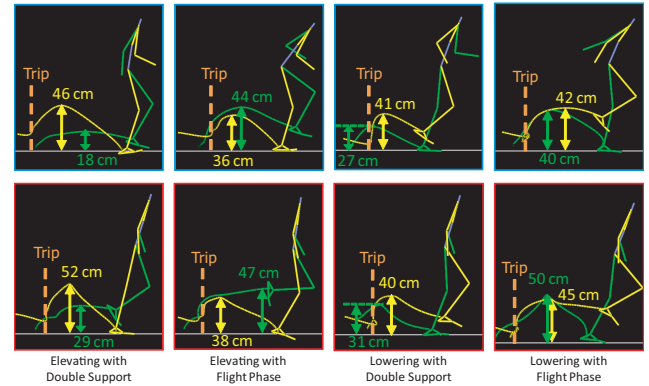


Figure 4. Comparison of foot trajectories and height between motion capture data and simulated motion. Top: motion capture data and bottom: simulated motion. Yellow and green lines were trajectories of tripped and non-tripped feet, respectively.

ering strategies were compared with motion capture data (Figures 2 and 3). Qualitatively, they were similar to the actual motions. Acceptable matches of the trajectories and height of the tripped/non-tripped foot were also produced (Figure 4).

## CONCLUSION

Responses to tripping were physically simulated based on motion capture data of tripping. In the future, we will collect more data to further develop and validate the simulation models. We will also extend our 2D simulation to 3D including arm movements. Finally, the long term goal of this work is to use the simulations to gain a better understanding of trip-triggered failed postural recovery responses in older adults.

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## ACKNOWLEDGEMENTS

This study has been supported in part by F31 AG025684-03 NIH Ruth L. Kirschstein Award and by NSF Quality of Life Technology Center.