The Influence of Walking Velocity and Response Time on the Ability to Avoid a Fall after a Trip

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Introduction
Older adults commonly use a "lowering" strategy to avoid a fall after a trip; the tripped foot is lowered to the ground and makes a rapid transition from swing to stance. For those who use this strategy, unsuccessful recovery has been associated with increased walking speed and slower response time (Pavol et al., in press). Since both variables contribute to the amount of body tilt at the time that the tripped (recovery) foot contacts the ground, it is important to identify whether walking speed and response time interact through this mechanism to determine trip outcome. If this is the case, the relative importance of these variables for fall prevention can be determined. Hence, we asked three questions: (1) Does tilt angle determine successful recovery? (2) Can a simple model predict this angle from walking speed and response time? (3) Is walking speed or response time more important in preventing a fall?

Methods
Walking speed, time to recovery foot ground contact ("response time"), and support ankle-to-body center of mass tilt angle as a function of time were measured during a trip in 79 safety-harnessed older adults, of which 34 used a lowering strategy (Pavol et al. 1999). Five of these 34 fell because they were not able to complete the recovery step. The tilt angle at time of recovery foot ground contact ("final tilt angle") was examined for its ability to predict successful recovery.

A single-link inverted pendulum model with inelastic collision was used to predict body rotation after the trip from walking speed, initial tilt angle, and inertial properties. Initial tilt velocity \( \omega_0 \) was solved from conservation of linear and angular momentum, assuming that the body rotates about the stance ankle after the trip:

\[
\omega_0 = \frac{mvd \cos \theta_0}{I + md^2 \cos^2 \theta_0}
\]

where \( v \) is walking speed, \( m \) is body mass, \( d \) the distance from center of mass to ankle joint, \( I \) the moment of inertia with respect to the center of mass, and \( \theta_0 \) the initial tilt angle. The falling movement was then predicted from initial tilt angle and angular velocity:

\[
\theta(t) = \theta_0 \cosh(kt) + \frac{\omega_0}{k} \sinh(kt)
\]

where

\[
k = \sqrt{\frac{mgd}{I + md^2}}
\]

and \( g \) is the acceleration of gravity. Assuming a thin rod with length \( h \) and uniform mass distribution, the inertial properties were approximated as \( d = h/2 \) and \( I = mh^2/12 \).

The model was validated by comparing the falling movement of each subject, from the time of trip to the time when the recovery foot contacted the ground, to the corresponding model prediction. Regression analysis was used to determine the correlation and root-mean-square (RMS) difference between predicted and measured tilt angle at the end of this time interval.

The model was used to perform three "experiments" in a hypothetical subject to determine the relative importance of walking speed and response time on success of recovery. First, the two variables were perturbed from the population mean by one standard deviation and the effects on final tilt angle were compared. Second, the mean of the five fallers was used as a starting point and the effects of altering the walking speed and response time to a normal value were compared. Third, the safe walking
velocity was determined for a person with the mean response time of the five fallers. It was then predicted by how much this person's safe walking velocity would increase by having a normal response time.

**Results**

Tilt angle at time of recovery foot contact was a perfect predictor of successful recovery. The smallest value among the five fallers was 26 degrees, the largest value in the 29 other subjects was 23 degrees. This suggests that recovery is only possible if the recovery foot is placed before the body tilt reaches the critical angle of about 25 degrees. Furthermore, the inverted pendulum model predicted the final tilt angle from walking speed and response time with an error of 0.4 ± 2.2 degrees and was equally effective at predicting successful recovery (Fig. 1). This was taken as an indication that the inverted pendulum model is a valid predictive tool.

In the first two model experiments, the model predicted that response time was more important than walking speed for success of recovery. In the third experiment, reduction of response time to a normal value allowed a 77% increase in safe walking speed in a typical individual who is at risk for falling (Fig. 2). The model predictions plotted in the speed-response time diagram may be used to easily perform additional hypothetical experiments.

![Graph](image)

**Figure 1:** Relationship between measured and predicted orientation of the body at the onset of weight bearing by the tripped foot. Arrows indicate subjects with a distinct deceleration of body rotation. A threshold body orientation of 25 degrees (dashed lines) perfectly separates the during-step fallers (○) from the subjects who recovered (＊) or fell after the step (+).

**Discussion**

The model was based on several assumptions, most importantly: the human body was modeled as a thin rigid rod and inelastic collision with the ground was assumed to initiate the falling movement. Nevertheless, the model was found to be valid for most subjects. Four subjects (indicated in Fig. 1) showed a distinct deceleration of the fall that was inconsistent with the inverted pendulum model. These
subjects had longer response times than normal, so caution is advised when applying the model to predict movements of longer duration. However, these limitations did not prevent the model from correctly predicting all five falls. With only five falls, there is some uncertainty whether there will be overlap in tilt angle between the fallers and non-fallers. More experiments are needed to answer that question.

Retrospective studies have typically found that risk of falling is associated with slow walking speed (Bath et al., 1999). Our model, supported by laboratory experiments, predicts an opposite relationship. We speculate that slow walking, as found in retrospective studies, might have been a protective adaptation to compensate for other risk factors.

Slow reaction time is a known risk factor for falls in older adults and can be improved by exercise (Lord et al., 1995). However, the response time measured in our experiments is task-specific and it is not known if reaction time improvements in other tasks will carry over to the tripping task.

In conclusion, the model can produce patient-specific recommendations for fall prevention, and therapeutic interventions should be directed at improving the response time of older adults.

References


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Figure 2: Illustration of the third model experiment. (1) Hypothetical subject with the average walking velocity and response time of the subjects who fell during the recovery step. (2) Reduction of walking velocity to the largest "safe" value predicted by the model. (3) Reduction of response time to the average of all subjects, followed by increase in walking velocity to the largest "safe" value predicted by the model. Shaded area indicates where model predicts a fall. This result shows that, in a typical person who is at risk for falling, safe walking velocity can almost be doubled when response time is improved.