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Mechanisms of failed recovery following postural perturbations on a motorized treadmill mimic those associated with an actual forward trip

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Abstract

Objective. To examine the recovery strategies employed during a treadmill acceleration task, to determine if mechanisms that contributed to failed recoveries on a motorized treadmill are the same general biomechanical mechanisms that contributed to falls from a trip, and to determine if failed recovery responses could be modified to allow for successful recoveries on subsequent trials.

Design. A motorized treadmill was used to induce postural perturbations in healthy older adults.

Background. Previously, we induced trips in older adults to identify the mechanisms of failed recovery. However, inducing trips is not a clinically practical test for identifying older adults who are predisposed to falling.

Methods. Safety-harnessed older adults stood on a treadmill that was accelerated from 0 to 0.89 m/s to impose a postural perturbation. Recoveries were classified as successful ($n = 42$) or failed ($n = 23$). Selected biomechanical variables were calculated using motion analysis methods.

Results. Initial failed recoveries had slower reaction times, shorter step lengths, and greater trunk flexion angles and velocities. Subjects who failed on the initial attempt modified their recovery strategy to successfully recover. The biomechanics of these recoveries resembled those used by subjects who successfully recovered on their initial attempt.

Conclusions. The biomechanical mechanisms involved with a failed treadmill recovery mimic those responsible for failed recoveries from an induced trip. Subjects who failed on their initial recovery response made modifications allowing successful recoveries on subsequent attempts.

Relevance

This protocol may be useful as a testing and rehabilitation tool for fall recovery.

Keywords: Falling; Older adults; Practice; Gait

1. Introduction

Falls in older adults are a major health concern that can lead to restriction of activity, injury, and death [1–3]. Based on these consequences, identification of older adults who are predisposed to falling has become a research imperative. Clinical tests that accurately identify the risk factors associated with falling are required so that effective therapeutic interventions can be designed and implemented.

We previously introduced a protocol in which trips were induced in older adults during gait [4]. Using this protocol we characterized the biomechanics of successful and failed recovery by older adults [5]. The factors associated with falls included body type and/or walking posture, response time, trunk flexion, and lower extremity buckling. Although this protocol has enhanced our understanding of biomechanical mechanisms associated with falls due to trips, the time and expense of administering the protocol precludes its widespread clinical use to determine risk factors or as a potential intervention.

The presently reported study is part of an effort to translate findings from our previous studies into a clin-

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ically relevant testing and rehabilitation tool. In this study we have used a motorized treadmill to impose large postural perturbations on older adults. The primary purpose of this study was to determine if the mechanisms that contributed to failed recoveries on a motorized treadmill would be the same general biomechanical mechanisms that contributed to falls from a trip. Recovery biomechanics were quantified by a variable set that included reaction time, step length of the initial recovery step, and the center of mass-to-recovery foot location, trunk flexion angle, and trunk flexion velocity at toe-off and at recovery foot ground contact. It was hypothesized that these variables would differ significantly between successful and failed recoveries during the initial recovery attempt on the motorized treadmill. The second purpose of the study was to determine if failed recovery responses could be modified to allow for successful recoveries on subsequent trials. It was hypothesized that the biomechanics of successful, modified recoveries would not differ significantly from those of the successful initial trials.

2. Methods

Fifty women and 29 men (mean age: 72 (SD 5) years; height: 1.64 (SD 0.09) m; mass: 76.0 (SD 14.0) kg) participated in this study, which was part of a larger study of falling in these older adults. All subjects were healthy, community-dwelling, and aged 65 years or older. Prior to acceptance, the subjects were examined by a geriatrician to identify the presence of exclusionary factors that included neurological, musculoskeletal, and cardiovascular disorders. The bone mineral density of the right femoral neck was assessed by dual-energy X-ray absorptiometry (Hologic QDR 1000, Waltham, MA, USA). A minimum value of 0.65 g/cm^2 was required for acceptance into the study. This value was considered to separate those at risk of hip fracture from those not at risk [6,7]. The study was approved by the Institutional Review Board and all subjects provided written informed consent.

The current study employed a motorized treadmill (Series 1800, Marquette Electronics, Milwaukee, WI, USA) to impose a postural perturbation to the standing subject [8]. The perturbation required anteriorly directed steps to regain balance. Subjects stood quietly upon the treadmill belt and were warned only that the treadmill would be activated ‘‘sometime in the next minute’’. Once activated, the treadmill accelerated to 0.89 m/s (2.0 miles per hour) in about 150 ms, independent of the subject's weight. Subjects were instructed that, when the treadmill started, they were to recover their balance and continue walking. Five recovery attempts were collected, with each trial lasting 5 s. The initial attempt was considered an ‘‘untrained’’ response.

A six-camera motion capture system (Motion Analysis, Santa Rosa, CA, USA), operating at 60 Hz, recorded the motion of 19 hemispherical passive reflective markers applied over selected anatomical landmarks of the bilateral upper and lower limbs, torso, head, and the treadmill belt. The three-dimensional trajectories of each marker were computed and selected biomechanical variables were derived.

Subjects were protected from falling by a safety harness (Dorsal C76, Petzl, Crolles, France). The harness was attached from the upper torso and pelvis of the subject to a ceiling-mounted track by a pair of dynamic ropes (11 mm diameter). The dynamic ropes, commonly used in rock and mountain climbing, were instrumented with a calibrated load cell (Omega Engineering, Stamford, CT, USA) that was connected in series with the ropes. The load cell data were collected at 250 Hz and stored for post-processing.

Failed recovery responses were identified visually and corresponded to the subject's hands touching the motor housing at the front of the treadmill or to the subject's body being completely supported by the dynamic ropes. The remaining recoveries were differentiated based on the extent of assistance provided by the dynamic ropes during the recovery, as determined from the force exerted through the instrumented dynamic ropes. The calibrated load cell signal was filtered at 8 Hz using a recursive fourth-order Butterworth low-pass filter. The filtered signal was expressed as a percentage of the subject's body weight and integrated for 1 s following activation of the treadmill. Recoveries that had an integrated force of greater than 5% body weight · second were classified as rope-assisted recoveries and eliminated from further analyses. All other recoveries were considered successful.

For each trial, three time points were identified by a computer algorithm and visually confirmed by the same investigator. The onset of treadmill motion was determined from the motion of the treadmill belt marker. Recovery step toe-off was determined as the onset of vertical motion of the marker placed over the fifth metatarsal head (‘‘toe’’) of the recovery foot. Recovery foot ground contact was determined to coincide with the earlier of the minimum vertical position of the recovery foot heel or toe marker.

Reaction time was determined as the time between the onset of treadmill motion and recovery step toe-off. Step length of the initial recovery step was determined as the change in the relative position of the recovery foot ankle marker with respect to the treadmill belt marker between treadmill activation and recovery foot ground contact. Step length was expressed as a percentage of body height. Body segment masses estimated from anthropometric measurements, body segment orientations determined from kinematic data, and assumed or computed center of mass positions within each body segment were used by a custom algorithm to determine the position of the whole-body center of mass [9]. The anteriorly directed horizontal distance in the sagittal plane from the body center of mass position to the ankle marker on the recovery foot was computed and normalized to the height of the subject. A positive body center of mass-to-recovery foot position indicates that the ankle marker of the recovery foot was located anterior to the body center of mass. Trunk flexion angle was computed as trunk rotation from vertical about an axis located at the level of L_3L_4 [5]. Trunk flexion velocity was computed as the derivative of the trunk flexion angle data.

For the initial attempt, independent *t*-tests were used to compare the selected variables of the subjects who successfully recovered to those who failed to recover. Variables for which the between-group differences were significant were entered into a stepwise discriminant analysis. For subjects failing to recover on their initial attempt, paired *t*-tests were used to compare the biomechanical variables of the failed initial recovery attempt to the modified biomechanics from the subject's subsequent successful attempt. The biomechanics of the successful, modified recoveries were also compared to those of the successful recoveries from the initial attempt using independent *t*-tests. All statistics were conducted using SPSS V7.0. A significance level of .05 was used in all analyses.

3. Results

Sixty-five subjects could be unambiguously classified as having performed a successful ($n = 42$) or a failed ($n = 23$) recovery on their initial attempt. Of the remaining 14 subjects, one was classified as a rope-assisted recovery and 12 had missing load cell or marker data. One subject failed to react to the accelerated treadmill, thus variables such as step length and reaction time could not be computed.

Differences between successful and failed recovery on the initial attempt could not be attributed to initial differences in body position. At the onset of treadmill motion, the between-group difference in the relative anterior–posterior position of the body center of mass was not significant ($P > 0.05$, Table 1). In addition, the differences in trunk flexion angle between the two groups were not significant ($P > 0.05$, Table 1).

Those subjects who failed to recover on their initial attempt had a slower reaction time than those who successfully recovered ($P < 0.05$, Table 1, Fig. 1). On average, the reaction time during the failed recoveries was 40 ms slower than the reaction time during the successful recoveries.

At the instant of toe-off, those subjects who failed to recover on their initial attempt had a body center of mass that was located more anterior to their recovery foot ankle marker and had a greater trunk flexion angle than those who successfully recovered ($P < 0.05$, Table 1). The differences in trunk flexion velocity at the instant of toe-off between the two groups were not significant ($P > 0.05$, Table 1).

Those subjects who failed to recover on their initial attempt took a shorter step than those who successfully recovered ($P < 0.05$, Table 1). On average, the step length in the failed recoveries was 4% body height (about 6.5 cm) shorter than in the successful recoveries.

At the instant of recovery foot ground contact, those subjects who failed to recover on their initial attempt had a body center of mass that was located more anterior to their recovery foot ankle marker than those who successfully recovered ($P < 0.05$, Table 1). On average, the recovery foot ankle was anterior to the body center

Table 1
The mean (SD) of the successful recovery group ($n = 42$) and the failed recovery group ($n = 23$) for the parameters during their initial attempt on the accelerated treadmill

	Successful	Failed	*P*-value	95% CI[a]	
				Lower	Upper
Reaction time (s)	0.24 (0.03)	0.28 (0.05)	0.001	−.05	−.01
Step length (% BH)	29.6 (6.3)	25.4 (7.7)	0.021	.6	7.7
COM-to-recovery foot at onset (% BH)	−3.5 (1.0)	−3.7 (1.1)	0.499	−.4	.7
COM-to-recovery foot at toe-off (% BH)	−11.8 (1.3)	−13.8 (2.1)	<0.001	1.0	3.0
COM-to-recovery foot at ground contact (% BH)	1.1 (3.9)	−4.6 (5.4)	<0.001	3.5	8.1
Trunk angle at onset (deg)	1.7 (2.3)	1.9 (2.8)	0.693	−1.6	1.0
Trunk angle at toe-off (deg)	12.6 (4.7)	18.9 (7.2)	0.001	−9.7	−2.9
Trunk angle at ground contact (deg)	30.3 (8.8)	45.8 (13.6)	<0.001	−21.9	−9.1
Trunk velocity at toe-off (deg/s)	155.5 (42.6)	175.5 (64.3)	0.188	−50.5	10.3
Trunk velocity at ground contact (deg/s)	−12.1 (36.1)	60.9 (45.6)	<0.001	−93.6	−52.5

COM = body center of mass, BH = body height, CI = confidence interval.
[a] 95% Confidence interval of the difference between the means.

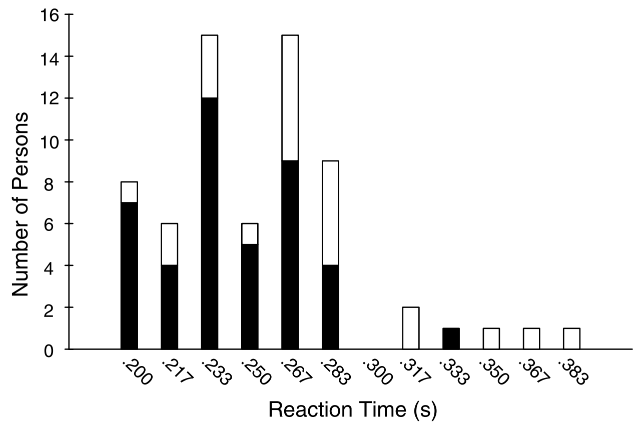

Fig. 1. Histogram of reaction times during the initial recovery attempt. The black bar (■) represents successful recoveries while the white bar (□) represents failed recoveries.

of mass at ground contact in the successful recoveries but posterior to the center of mass in the failed recoveries.

At the instant of recovery foot ground contact, those subjects who failed to recover on their initial attempt had a greater trunk flexion angle and a greater trunk flexion velocity than those who successfully recovered ($P < 0.05$, Table 1). The trunk flexion angle during a failed recovery was, on average, 15° greater than during a successful recovery. The difference in trunk flexion velocity between the two groups was, on average, 70° per second.

The subjects who recovered and failed on the initial trial were discriminated statistically using trunk flexion angle at toe-off and trunk flexion velocity at recovery foot ground contact. The discriminant function was significant ($P < .001$, Wilks' Lambda = 0.51). The overall classification rate was 81.5% (34/42 successful and 19/23 failed recoveries).

Subjects could be placed into one of the three categories based on success rate over the five recovery attempts. All 42 subjects who successfully recovered on their initial attempt successfully recovered on their subsequent four attempts. Of the 23 subjects who failed on their initial attempt, 18 successfully recovered on their subsequent four attempts. The remaining five subjects were considered multiple fallers. One subject failed on 2 of the 5 attempts and three subjects failed on 3 of the 5 attempts. The other multiple faller terminated the protocol after the second attempt. A complete data set of the biomechanical variables during the failed attempt and the first subsequent successful attempt could be obtained for 20 of the 23 fallers.

At the onset of treadmill motion, the differences in the location of the whole-body center of mass between the failed, initial recovery attempt and the successful, modified recovery attempt were not significant ($P > 0.05$, Table 2). Also, the differences between the two attempts in trunk flexion angle at the onset of treadmill motion were not significant ($P > 0.05$, Table 2).

Subjects who failed to recover on their initial attempt successfully modified their subsequent recovery by having a faster reaction time ($P < 0.05$, Table 2). Reaction time during a modified recovery was, on average, 50 ms faster than during the failed recovery.

Compared to failed recoveries, the body center of mass during successful recoveries was less anterior to the ankle marker at toe-off during the modified recoveries ($P < 0.05$, Table 2). Also at toe-off, there was a decrease in trunk flexion angle and trunk flexion velocity during the modified recoveries compared to the failed recoveries ($P < 0.05$, Table 2).

Subjects who failed to recover on their initial attempt successfully modified their subsequent recovery by taking a longer recovery step ($P < 0.05$, Table 2). Step

Table 2
The mean (SD) of the parameters during the failed initial attempt and the first subsequent successful attempt ($n = 20$)

	Failed	Successful	*P*-value	95% CI[a]	
				Lower	Upper
Reaction time (s)	0.28 (0.05)	0.23 (0.03)	<0.001	.03	.07
Step length (% BH)	25.3 (8.1)	34.3 (7.5)	<0.001	−12.8	−5.3
COM-to-recovery foot at onset (% BH)	−3.7 (1.1)	−3.6 (1.1)	0.700	−.4	.3
COM-to-recovery foot at toe-off (% BH)	−13.9 (2.2)	−11.5 (1.5)	<0.001	−3.3	−1.3
COM-to-recovery foot at ground contact (% BH)	−4.8 (5.7)	4.7 (3.6)	<0.001	−11.6	−7.4
Trunk angle at onset (deg)	1.9 (3.0)	2.5 (2.3)	0.360	−2.0	.7
Trunk angle at toe-off (deg)	19.1 (7.2)	11.2 (5.0)	<0.001	5.1	10.8
Trunk angle at ground contact (deg)	44.8 (13.0)	28.5 (7.8)	<0.001	12.3	20.4
Trunk velocity at toe-off (deg/s)	174.3 (64.8)	146.1 (47.5)	0.005	9.5	46.9
Trunk velocity at ground contact (deg/s)	59.2 (46.6)	−20.3 (42.5)	<0.001	53.7	105.3

COM = body center of mass, BH = body height.
[a] 95% Confidence interval of the difference between the means.

length, on average, was 9% body height longer during a modified recovery than during the failed recovery.

Compared to failed recoveries, the body center of mass was less anterior to the ankle marker at recovery foot ground contact during the modified recoveries ($P < 0.05$, Table 2). Also at recovery foot ground contact, there was a decrease in trunk flexion angle and trunk flexion velocity during the modified recoveries compared to failed recoveries ($P < 0.05$, Table 2).

Differences between the biomechanics of successful recoveries during the initial attempt (successful column, Table 1) and the biomechanics of modified recoveries during a subsequent attempt (successful column, Table 2) were not significant for eight of the 10 variables (all $P > 0.05$). Only step length and relative body center of mass location at recovery foot ground contact were significantly different ($P = 0.012$ and $P = 0.001$, respectively). Compared to successful recoveries, modified recoveries produced a larger step length and an accompanying body center of mass location that was more posterior to the ankle marker.

4. Discussion

In this study, acceleration of a motorized treadmill was used to apply a large postural perturbation to standing older adults. A similar perturbation might be experienced by a standing passenger during the sudden deceleration of a bus or train. While the recovery responses to support surface accelerations during standing have been widely studied [10–13], two factors make the present protocol unique. First, the perturbation was large enough to produce failed recoveries, allowing the associated mechanisms to be studied. Second, successful recovery required establishing a stable pattern of gait. As such, the task of recovery for the present protocol might reasonably be comparable to that for a trip.

The primary purpose of this study was therefore to determine if mechanisms that contributed to failed recoveries on a motorized treadmill would be the same general biomechanical mechanisms that contributed to falls from a trip. The factors associated with falls from an induced trip [5] included a delayed response time, a more anteriorly located center of mass at the time of the trip and at recovery foot ground contact, and greater trunk flexion and faster forward rotation of the head–arms–torso about the hips at recovery foot ground contact. For the present study, failed recoveries on the motorized treadmill, when compared to successful recoveries, had a slower reaction time, a more anteriorly located center of mass location at toe-off and at recovery foot ground contact, greater trunk flexion at toe-off and at recovery foot ground contact, a greater trunk flexion velocity at recovery foot ground contact, and a shorter recovery step length. The similarities between the type of mechanisms leading to a failed recovery on a motorized treadmill and the type of mechanisms contributing to falls from a trip suggest that the treadmill test has the potential to be developed and used as a clinical tool.

The second purpose of the study was to determine if failed recovery responses could be modified to allow for successful recoveries on subsequent trials. We expected that the biomechanics of successful, modified recoveries would resemble those of the initial successful trials. Subjects who failed in their initial recovery attempt successfully recovered in later attempts by adopting a response that closely approximated that of the subjects who were successful in their initial attempt. Compared to the failed recovery, the successful, modified recovery had a faster reaction time and an increased length of the initial recovery step, resulting in a less anterior center of mass location at toe-off and at recovery foot ground contact, a decreased trunk flexion angle at toe-off and at recovery foot ground contact, and a decreased trunk flexion velocity at toe-off and at recovery foot ground contact.

Prior to treadmill activation, the differences in trunk angle or in the anterior–posterior body center of mass location between the failed and the successful recovery groups were not significant. This indicates that the groups were not different in their initial standing postures. Thus the failed recovery group was not predisposed to falling by their initial standing posture.

Subjects with a delayed reaction time place themselves at a disadvantage for a successful recovery. Following the activation of the treadmill, but prior to the initiation of the stepping response, subjects resemble an inverted pendulum. The posterior motion of the feet causes the body center of mass to be displaced anteriorly to the base of support (i.e., the feet) and increases the trunk flexion angle relative to the vertical position. Thus, as seen in the differences between the successful and failed recovery groups at toe-off, a delayed reaction time causes subjects to have a more anteriorly located body center of mass and a greater trunk flexion angle at the initiation of the stepping response which increases the difficulty of the recovery task. It is interesting to note that four of the six subjects with the slowest reaction times were multiple fallers (Fig. 1). Since these subjects required multiple attempts before executing a successful recovery, it is possible that reaction time for this task is not as easily modified as other recovery factors.

However, having a sufficient reaction time in response to the treadmill activation did not ensure a successful recovery (Fig. 1). Forty-one of 42 subjects who successfully recovered in their initial attempt had a reaction time less than 300 ms, yet 18 of 23 subjects who failed to recover also had reaction times less than 300 ms. The similar reaction times and dissimilar outcomes point to the multifactorial nature of successful recovery during the treadmill task.

Successful recoveries are also reliant on the appropriate positioning of the stepping foot in relation to the body center of mass. Taking a longer step places the foot in front of the body center of mass so the limb can act to slow forward body rotation and re-establish dynamic balance. Conversely, a short step will most probably place the foot behind the body center of mass, causing an increased forward rotation and thereby making recovery more difficult. The dissimilar outcomes that result from similar positioning of the stepping foot in relation to the body center of mass (0% to −7% body height, Fig. 2) indicate the multifactorial nature of the recovery task.

Although there is a multifactorial nature to the recovery tasks, two trunk kinematic variables emerged as determinants for distinguishing successful and failed recoveries. The discriminant analysis identified trunk flexion angle at toe-off and trunk flexion velocity at recovery foot ground contact as the discriminating variables of greatest value. The ability to restore control of the flexing trunk has previously been identified as a dependent variable for fall recovery [14]. As stated previously, interventions for controlling trunk flexion may rely primarily on modifications in reaction time and step length.

Subjects who failed on their initial recovery response were able to modify their recovery strategy and successfully recover on a subsequent attempt. These subjects modified their recovery strategy to resemble those subjects who were successful on their initial attempt. For these subjects, the appropriate adaptations were made acutely and without external intervention, such as strength or balance training. This indicates that each subject already possessed the components to successful recovery and that the failed recovery reflected a failure to appropriately integrate, or coordinate, the components. If, indeed, the ability to recover from a perturbation is primarily a matter of coordination, training of the stepping response to large perturbations may be the most effective intervention in preventing falls by older adults.

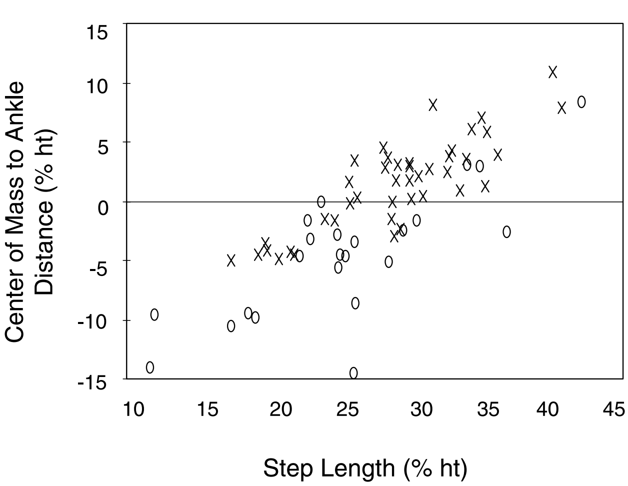

Fig. 2. Distance, measured anteriorly, from the body center of mass to the recovery foot ankle marker at recovery foot ground contact versus step length for the successful (X) and failed (0) recoveries during the initial recovery attempt.

There seem to be multiple variables that contribute to a successful recovery, such that a continuum of reactive balance strategies was employed in response to a similar perturbation. Although no single variable can presently be attributed with greater importance, it seems that the coordination of these variables dictates successful recovery. Coordinating an appropriate reaction time with a sufficient recovery step length, while maintaining control of trunk motion, seem to be the important elements for a successful recovery strategy.

An advantage of the treadmill protocol is that subjects may be repeatedly surprised by the imposed perturbation, thus allowing recovery strategy modification to be investigated. Although the long-term effects of the recovery modifications are not known at this time, we believe that this protocol has the potential to be developed and used clinically as a testing device, and/or as a means of training, for older adults who may be predisposed to falling.

Although subjects were able to modify their recovery strategy, we cannot discount the possibility that there may have been an added proactive balance adjustment, such as trunk stiffening after the initial attempt. However no changes in initial posture or physical readiness were outwardly apparent across trials. Future studies could confirm this by using electromyographic methods.

It is also possible that prior experiences with similar perturbations, such as in riding public transport, might have influenced the responses of some subjects in the present study. We cannot state how many subjects may have had such experience. Based on our results, this factor could have influenced the rate of successful recoveries in the initial attempt, but would have had little effect on the biomechanics of these recoveries.

A benefit of the motorized treadmill used in the present study was its ability to rapidly accelerate. However, a shortcoming of the treadmill is that it was not instrumented to allow more accurate determination of reaction time and recovery step toe-off and ground contact. These were identified from motion data that were collected at 60 Hz, limiting the resolution to increments of 0.017 s. Use of a computer algorithm eliminated any biases associated with identifying the times of interest, although a systematic error is still possible. Since all of our subjects were assessed using the same methods, these limitations should not influence the results of this study. Nevertheless, because reaction times were measured to step toe-off, they will greatly exceed those based on force changes or electromyography. Greater resolution of reaction time and other time points is desirable in the future.

5. Conclusion

The mechanisms that contributed to failed recoveries on a motorized treadmill mimic the general biomechanical mechanisms that contributed to falls from a trip. Modifications were made by those subjects who failed on their initial recovery response enabling them to successfully recover on a subsequent attempt. The potential for this type of protocol as a testing and rehabilitation tool for recovery from large postural perturbations in older adults merits systematic study.

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