Endocrine, *vol. 17, no. 1, 15–20, February 2002* 0969–711X/02/17:15–20/$11.50 © 2002 by Humana Press Inc. All rights of any nature whatsoever reserved.

Can Fall-Related Hip Fractures Be Prevented by Characterizing the Biomechanical Mechanisms of Failed Recovery?

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Unintentional injuries are the seventh leading cause of death in adults ages 65 and older, and the greatest number of these deaths results from fall-related injuries. In addition to the startling mortality, the morbidity associated with fall-related injuries, particularly hip fractures, has become a research imperative. This article reviews a series of studies that was undertaken to determine the biomechanical reasons that older adults are unable to recover from very large postural perturbations that are applied during locomotion that, if not corrected, can lead to a fall. Our protocol involves causing older adults to trip unexpectedly while walking normally in the laboratory. The results from this series of experiments were used to design an experiment that characterized the biomechanical similarities between recovery biomechanics after an induced trip and those following a large postural perturbation delivered by a motorized treadmill. Collectively, we have been able to document different recovery strategies and categories of falls by older adults following an induced trip; the biomechanical causes of these falls by older adults; and the very rapid motor adaptations that occur with repeated exposure to large perturbations that may be protective against falls from tripping and, therefore, reduce the substantial fall-related morbidity and mortality in older adults.

Key Words: Aging; biomechanics; falls; hip fracture; intervention.

Introduction

In older osteoporotic adults, fall prevention is the mechanism having the greatest probability of reducing the number of fractures *(1)*. Prevention of hip fractures, one of the most physically disabling fall-related injuries an older adult can experience, has become a research imperative. Ninety percent of the 300,000 hip fractures occurring annually in the United States are a result of falls by older adults *(2)*. Fall-related fractures are not limited to the hip, however. Although associated with substantially less morbidity than hip fracture, a similar number of fractures in older adults that affect the wrist, forearm, and arm *(3)*. Beyond these injuries and the deleterious psychologic impact that even noninjurious falls can impart, falls account for a startling level of mortality in older adults. In 1997, nearly 10% of all unintentional injury deaths in the United States resulted from falls by older adults *(4)*. Hip fracture increases the mortality rate up to 20% compared to age-, sex-, and race-matched adults *(5)*. In light of the expected and substantial increase in the worldwide population of older adults, fall-related injuries and costs will increase dramatically.

Healthy People 2000 was a decade-long national health promotion and disease prevention program in the United States during the 1990s. The program addressed 45 objectives, 26 of which were in the category of unintentional injury prevention. One objective for which no progress was made was a reduction in the hospitalization rate for hip fractures. An approach to reducing the number of fall-related hip fractures in older adults has been to identify treatable risk factors for falls. Some untreatable risk factors include age, previous fracture, maternal history of hip fracture, height as a young adult, dementia, late menarche, long hip axis length *(6)*, and peripheral neuropathy *(7)*. However, there are numerous risk factors for hip fracture that are potentially treatable *(8)*, such as low bone mass, smoking, impaired vision, long-acting sedatives, caffeine, physical inactivity, poor health, Parkinson disease, low body weight, and little exposure to sunlight *(6)*.

Other physiologic risk factors that are candidates for intervention have been the focus of concerted effort. There are intuitively attractive associations between age-related reductions in muscle strength, muscle power, and postural control, and the parallel age-related increase in falls. These associations have been a motive force behind exercise-based interventions. However, the effectiveness of exercise interventions is not entirely clear. Some opinions regarding exercise interventions reflect hesitancy *(9–11)*, whereas others, such as those of the Surgeon General of the United States *(4)* and the American College of Sports Medicine *(12)*, have promoted more positive conclusions.

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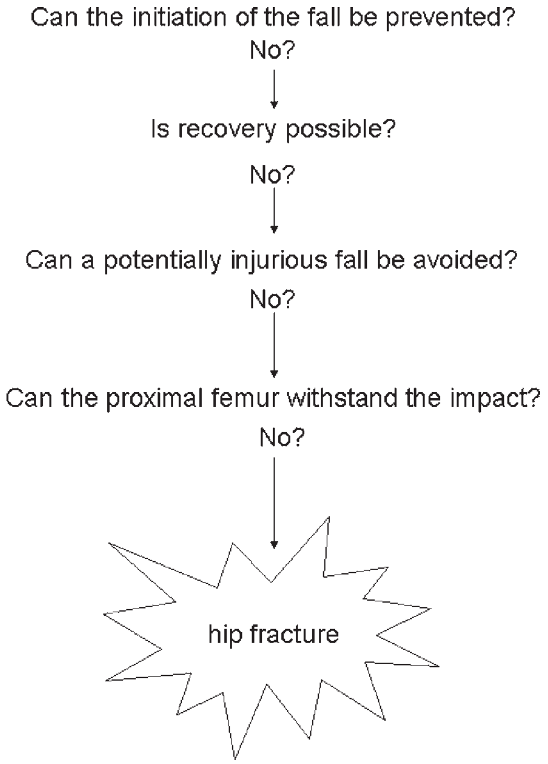

Fig. 1. Conceptual model of sequence of events leading to fall-related hip fracture. (Adapted from ref. *5*.)

Hierarchy of Events That May Lead to a Hip Fracture

A conceptual model that considers many of the factors that cause hip fracture can be arranged to form a hierarchical sequence of events (Fig. 1). In this model, hip fracture results from of a sequence of biomechanical failures that begin at the organismic level and end at the organ level. At the organismic level, failures in neuromuscular processes can result in the initiation of a fall and a subsequent inability to recover. Whether the impending fall will result in hip fracture is strongly influenced by the biomechanics of impact. The likelihood of a hip fracture substantially increases if the fall results in an impact near or on the greater trochanter, since the resulting impact energy will be directed through the femoral neck. Once impact has occurred, the structural properties of the proximal femur determine whether the energy of impact will produce a fracture. The structural properties include the material properties of the bone tissue, often represented by bone mineral density (BMD), as well as the size and shape of the bone. The importance of structural properties of the proximal femur, in general, and BMD, in particular, as the last line of defense against fall-related hip fractures underscores the importance of fall prevention to osteoporotic men and women, in whom this line of defense is compromised.

The primary form of fall prevention, which occurs at the organismic level, is the avoidance of those circumstances that cause fall initiation. If there is no fall, epidemiologic statistics suggest that 90% of hip fractures may be precluded. Up to half of falls leading to hip fracture are initiated by some type of external perturbation *(13,14)*, as opposed to internal perturbations such as syncope. Preventing the initiation of a fall following an external perturbation is reliant on recovery strategies. An ankle strategy, during which the body acts primarily as an inverted pendulum, counteracts slowly applied, low-magnitude perturbations during standing. The hip strategy, during which the body acts primarily as a two-segment inverted pendulum, counteracts larger, more rapidly applied perturbations. A hip strategy will likely be used if the dimensions and firmness of the supporting surface are insufficient to accommodate the plantarflexion reaction forces required for an ankle strategy. If an ankle or a hip strategy is insufficient to restore postural stability, or if a perturbation occurs during gait, a stepping response is necessary to prevent a fall. The success of the stepping response is reliant on physiologic resources that go well beyond those of the initial reflexive responses to the postural perturbation *(15)*.

Depending on the direction and magnitude of the postural perturbation, the successful performance of a stepping response can be a physically demanding motor skill for older adults. Stepping responses may require combinations of large amplitude, forceful movements, and coordinated motion of multiple body segments in a brief period of time. The published literature is replete with reports of independent variables associated with falls by older adults, most derived from retrospective cross-sectional studies. There are fewer prospective studies. Most relevant experiments reported in the literature have focused on the biomechanics of successful stepping responses *(16–21)*. Among the few reported characterizations of unsuccessful stepping responses *(22–24)*, until recently, none directly concerned falls by older adults during gait.

Experiments on the Biomechanics of Trip-Related Falls

To determine the biomechanics of unsuccessful recovery, safety-harnessed older adults were caused to trip unexpectedly while walking “normally” in the laboratory *(25)* (Fig. 2). Trips were studied because trip-related falls may account for as many as 20% of hip fractures *(13,26)*. In the protocol, which simulated a prospective experimental design, subjects expected to be tripped by a decoy rope placed across the floor and over which they had to step. However, the trip was induced 1.5 m beyond the decoy rope by a pneumatically powered mechanical obstacle. The presence of the mechanical obstacle was unknown to the subjects. When disengaged, the top of the mechanical obstacle was flush with the floor. When engaged, the obstacle rose 5 cm from the floor in about 170 ms. Kinematic and ground reaction data, acquired from six synchronized video cameras and from force plates, respectively, were used to test hypotheses related to factors proposed as critical to the success or failure of the stepping responses.

The experiments were performed on 79 older adults (50 women) who were carefully screened, independent community dwellers ranging in age from 65 to 86 yr. In addition to the described trips, a battery of tests measuring static and dynamic postural steadiness and control, and static and dynamic lower extremity muscle strength and power, was administered to these older adults. This protocol was a departure from a true prospective design since, rather than measuring the incidence of falls over a period of time, the trips in these older adults were induced. Furthermore, the tripping stimulus and the elapsed time between the administration of the battery of tests and that of the tripping protocol was similar for all subjects.

A key result of this study, which confirmed the findings of epidemiologic studies, was that the incidence of falls by older women was significantly greater than that of older men. Proportionately, approximately four times as many women as men fell. Since each subject was presented with the same tripping stimulus, this result suggests that the reason women fall more often than men is not that they trip more often. Rather, there may exist a gender-specific variable(s) that renders women less capable of executing a successful recovery.

Further analysis revealed that 94% of the trip outcomes were correctly classified based on kinematics of self-selected “normal” gait *(27)*. In particular, a faster walking speed, longer stride length (relative to body height), and more rapid stride rate independently contributed to an increased likelihood of falling after the trip (odds ratios of 2.6, 3.5, and 3.5, respectively), for changes of 1 SD. This was interesting in light of the report that 31% of falls by older adults have been attributed, via self-report, to “just hurrying too much” *(28)*. Nevertheless, the findings of this analysis could not elucidate the mechanisms underlying the falls of the older adults who demonstrated this particular type of gait. A subsequent analysis therefore sought to identify the mechanisms of falling.

Older adults employed two primary recovery strategies after the trip *(29)*. The strategies differed regarding to the recovery foot (and limb) used to negotiate the obstacle *(17)*. An elevating strategy uses the foot that was tripped as the recovery foot. By contrast, a lowering strategy involves lowering the tripped foot to the ground and using the contralateral limb to negotiate the obstacle. A lowering strategy was used in 70% of recovery attempts, including eight of nine recorded falls.

There were two categories of fallers in the group of subjects who used a lowering strategy. The instant of the “fall” was defined to occur when the safety harness supported 50% of a subject’s body weight. Based on this criterion, one group of five subjects was identified who “fell” within 80 ms of when the recovery foot contacted the ground. These subjects were referred to as “during-step” fallers (Fig. 2, top). By contrast, a second group of three subjects did not “fall” until more than 400 ms after the recovery foot contacted the ground. These subjects were referred to as “after-step” fallers (Fig. 2, bottom).

The mechanisms underlying during-step falls and after-step falls were different *(29)*. During-step fallers were walking significantly faster than those subjects who recovered and had a significantly longer “reaction time,” measured as the time taken to lower the tripped foot to the ground. The combination of a faster walking velocity and a longer reaction time conspired to place the during-step fallers in a biomechanically disadvantaged position in which the lowered limb could not be used to arrest the trip-induced forward body rotation. This biomechanically disadvantaged position was characterized by the center of mass of the head-arms-trunk segment being located anteriorly to the ground reaction vector.

Unlike the during-step fallers, the after-step fallers were not walking faster than those who recovered. Instead, the center of mass of the after-step fallers’ head-arms-trunk segment was more anteriorly located at the time of the trip, largely owing to a more kyphotic posture. The result of this body state was a decreased ability (i.e., less available time) to decelerate the forward rotation of the body. After the recovery foot contacted the ground, after-step fallers were unable to arrest the forward rotation of the trunk or prevent the recovery limb from buckling during stance.

The failure of the after-step fallers to arrest the forward rotation of the trunk supported the hypothesized importance of trunk control to recovery *(30)* and arguably reflected inadequate trunk extension strength and/or power. Furthermore, the buckling of the recovery limb could reflect diminished hip and knee extensor muscle strength and/or power. Our results revealed that both the weak older adults and the very strongest older adults in the sample were at greater risk of falling from a trip, although by different mechanisms. High strength increased the likelihood of a during-step fall; decreased strength increased the likelihood of an after-step fall *(31)*. The former relationship reflects the finding that a faster walking speed was a primary cause of the during-step falls. In older adults, faster walking speed and longer steps during normal gait are associated with greater plantarflexion and knee extension strength *(32–34)*. These are essentially the factors for which the during-step fallers exhibited greater strength. By contrast, two of three after-step fallers were among the weakest subjects tested, consistent with a direct contribution of hip and knee extensor weakness to after-step falls, as was suggested earlier.

The findings from the studies in which older adults were tripped established a framework for investigating their clinical utility. For example, during-step fallers were walking significantly faster when tripped and had a significantly longer reaction time than subjects who did not fall. Biomechanically, walking velocity contributes to the forward angular

Fig. 2. In the sequences of induced trips, proceeding from right to left, the subjects are protected from falling to the ground by an instrumented harness. During the swing phase of the right leg (sequence at the top) and the left leg (sequence at the bottom), an obstacle rises from the floor and causes the women to trip. (**Top**) The recovery effort by this older woman was not successful. However, the fall would not expose the hip to impact, making a hip fracture unlikely. (**Bottom**) The recovery effort by this woman was not successful but, unlike the woman in the top panel, this woman completed a recovery step across the obstacle before "falling." Note that, in this case, impact on or near the left hip appears imminent. A hip fracture could potentially have resulted were the harness not present.

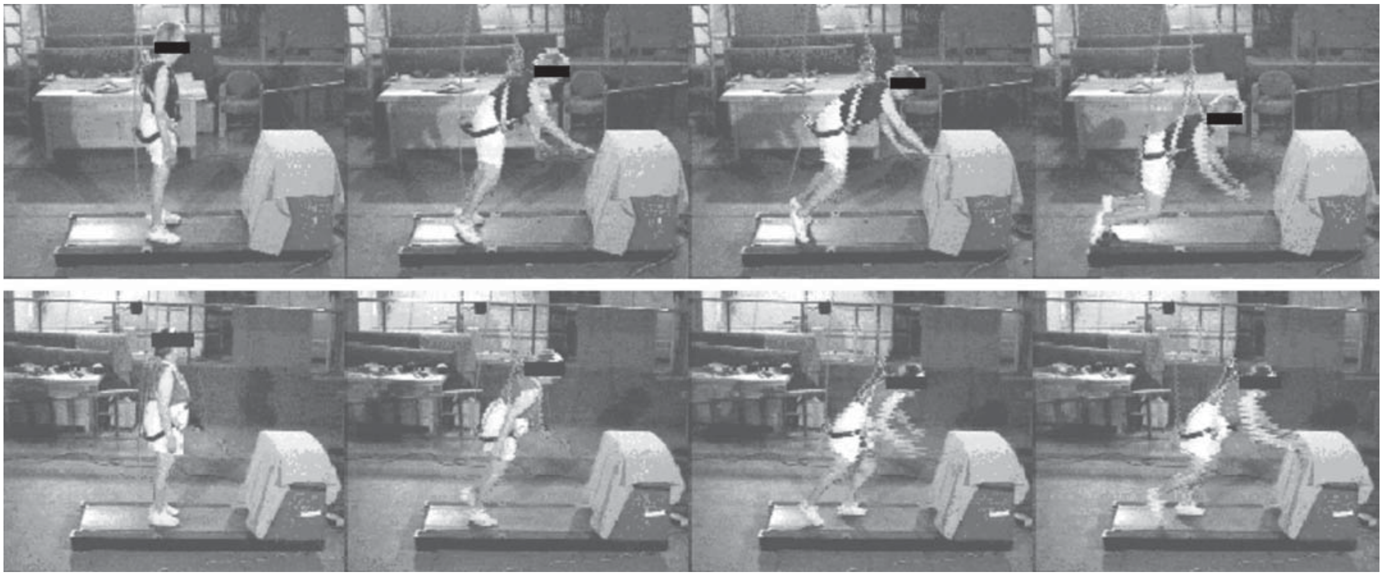

Fig. 3. In the sequences of treadmill-induced postural perturbations, subjects are protected from falling to the ground by an instrumented harness. (**Top**) The recovery effort by this older woman was not successful owing to a complete failure to initiate a recovery step. This represents an extreme case of a failed recovery that resulted from a longer reaction time. (**Bottom**) The recovery effort by this woman was not successful and primarily resulted from an insufficient recovery step length.

velocity of the body after the trip. Reaction time determines the angular distance through which the body rotates before recovery is initiated. Both factors represent possible targets for intervention. Reducing the incidence of trip-related falls by simply prescribing a slower walking velocity is attractive. Such a solution could be administered at the population level both quickly and inexpensively. By contrast, improving reaction time for a complex motor skill is a more difficult, time-consuming, and expensive undertaking. Yet, the potential effectiveness of these two possible interventions must also be considered. The experimental data do not allow this determination. Therefore, a computer simulation approach was used *(35)*.

A simple inverted pendulum model of the body's motion after a trip was used to determine whether reducing walking velocity was more effective than reducing reaction time in preventing a during-step fall. A key result of the simulations was the finding that reaction time was a more important determinant of trip outcome than was walking velocity. The general, and clinically challenging, implication is that decreasing the risk of falling following a trip can be better achieved by improving reaction time than by reducing walking velocity. The simulations indicated that if reaction time could be reduced from the during-step fallers' average of 267 ms to the population average of 175 ms, the maximum safe walking velocity for avoiding a trip-related fall would increase by 77%. The importance of these findings with respect to reaction time was consistent with the findings of Smeesters et al. *(24)*.

Having experimentally determined a set of biomechanical variables that may be causally linked to falls following a trip, the next determination was whether the motor skills associated with successful recovery can be enhanced in older adults. Clinical use of the previously described laboratory setup to train older adults to recover from a trip would not be practical. An effective protocol should not only possess specificity but must also be capable of being administered on a larger scale in a time- and cost-effective manner. One potential protocol that meets these latter criteria involves the use of a motorized treadmill to provide the large postural perturbation to which a stepping response is necessary *(36)*.

To investigate the utility of such a treadmill-imposed perturbation, a study was conducted with the same 79 older adults who participated in the tripping study. The first purpose of the study was to determine the extent to which the mechanisms of failed recoveries on the treadmill would be similar to the mechanisms of failed recoveries following a trip. The second purpose was to determine whether multiple exposures to the treadmill perturbation would result in altered recovery biomechanics and an increased recovery rate.

Safety-harnessed subjects stood on a motorized treadmill that, once activated, accelerated to 0.89 m/s (2.0 mph) in about 150 ms, independent of the subject's weight (Fig. 3). Subjects were instructed that, when, without warning, 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.

The mechanisms of failed recovery by older adults following the treadmill perturbation were similar, in general, to those associated with falls after an induced trip. These mechanisms included a longer reaction time, a more anteriorly located center of mass at recovery foot ground contact, and greater trunk flexion and trunk flexion velocity at recovery foot ground contact in the failed vs successful recoveries. Compared with successful recoveries, failed recoveries on the treadmill were also associated with a more anteriorly located center of mass at toe-off, greater trunk flexion at toe-off, and a shorter recovery step length.

On repeated exposure to the perturbation, all subjects who failed in their initial recovery attempt learned to recover successfully. Learning was rapid; of the 23 subjects who failed initially, 18 were successful in their second attempt. The modified recovery responses closely approximated the successful initial recoveries. Specifically, the successful, modified recoveries were marked by a faster reaction time, increased recovery step length, smaller trunk flexion angle at toe-off and at recovery foot ground contact, and smaller trunk flexion velocity at toe-off and at recovery foot ground contact, as compared with the failed initial attempt. Collectively, these findings suggest the potential for developing and using the protocol as a clinical tool.

Conclusion

Although substantial effort has been invested by members of the scientific and clinical communities, prevention of fall-related hip fractures in older adults remains a research imperative. Because of the multifactorial nature of fall-related fractures, effective fall prevention undoubtedly requires a multifactorial approach. Addressing the biomechanics of failed recovery is arguably an important component of this approach. Our results have shown that study of the biomechanics of successful and failed recovery can yield important and unique insights into how falls occur and how they may be prevented. Although still in its infancy, the possibility of reducing the incidence of falls by training the motor responses to large postural perturbations appears to have promise. Much is yet to be learned regarding the biomechanics of failed recovery and how these biomechanics may be applied to reducing the incidence of hip fracture in older adults.

Acknowledgment

This work was funded by Grant NIH-R01AG10557.

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