Department of Veterans Affairs

JRRD Volume 45, Number 8, 2008
Pages 1237–1248
Journal of Rehabilitation Research & Development

Regulation of angular impulse during fall recovery

Witaya Mathiyakom, PT, PhD;[1–3]* Jill L. McNitt-Gray, PhD[3–5]

[1]Department of Physical Therapy, California State University, Northridge, CA; [2]Physical Medicine and Rehabilitation Service, Department of Veterans Affairs Greater Los Angeles Healthcare System, Los Angeles, CA; Departments of [3]Kinesiology, [4]Biomedical Engineering, and [5]Biological Sciences, University of Southern California, Los Angeles, CA

Abstract—Maintaining balance and postural stability while performing functional activities is critical to an individual's independence and quality of life. When individuals are unable to maintain their total-body center of mass (COM) within the base of support, a loss of balance may result, leading to a fall. Effective interaction between the environment and the neuromuscular and musculoskeletal systems allows an individual to generate the ground reaction forces relative to the COM necessary for maintaining and recovering balance during expected and unexpected situations. This article reviews the role of the swing and support legs in regulating angular impulse during fall recovery and contrasts the balance recovery strategies used by younger adults and older adult nonfallers and fallers. Multijoint dynamics and neuromuscular control used during fall recovery are discussed at the total-body, joint, and muscle levels. Understanding the fall recovery mechanisms successfully used by younger and older adults will allow us to begin to identify effective intervention strategies that target specific populations.

Key words: aging, angular impulse, balance control, center of mass, fall recovery, ground reaction force, linear impulse, lower-limb kinetics, multijoint control, muscle activation pattern.

INTRODUCTION

Maintaining balance and postural stability while performing functional activities is critical to an individual's independence and quality of life. Effective interaction between the environment and the neuromuscular and musculoskeletal systems allows an individual to generate the ground reaction forces (GRFs) necessary for maintaining and recovering balance during expected and unexpected situations. As one ages, alterations in the nervous and/or musculoskeletal system capabilities introduce age-related deficits that may influence how an individual plans and executes activities of daily living.

Postural control during bipedal gait imposes a significant challenge to the nervous and musculoskeletal systems. In general, normal bipedal human gait consists of a series of single- and double-leg stance phases. The duration of the single-leg stance is approximately 40 percent of a gait cycle [1]. During the single-leg stance, the total-body center of mass (COM) is vertically positioned at approximately one-half of the body's standing height above the foot and moves along a horizontal trajectory of approximately 0.5 to 0.6 m within a step cycle. During single-leg stance, the support leg simultaneously supports the weight of the upper body (head, arms, and trunk) [1], helps control upper-body trajectory in both anteroposterior and mediolateral directions [2–3], and generates and redirects the GRF to propel the COM in the desired direction

Abbreviations: COM = center of mass, GRF = ground reaction force, NJM = net joint moment.

***Address all correspondence to Witaya Mathiyakom, PT, PhD; Department of Physical Therapy, California State University, Northridge, 18111 Nordhoff St, Northridge, CA 91330; 818-677-3108; fax: 818-677-7411.**
Email: witaya.mathiyakom@csun.edu
DOI: 10.1682/JRRD.2008.02.0033

[1–2,4]. The ability to reliably and safely execute bipedal gait often becomes compromised when an individual encounters age-related deficits and/or perturbations that interfere with linear and angular impulse regulation during stance [5–6]. An individual's inability to maintain and recover balance when perturbed during gait results in falls [5,7].

Regulation of angular impulse is an essential aspect of balance and fall recoveries. External perturbations applied to the body during gait, as observed during trips or slips, increase the angular momentum of the body [7–8]. Neutralizing the angular momentum introduced by an external perturbation requires that sufficient angular impulse be generated during the fall recovery phase so that control of the COM relative to the base of support is restored [5]. The direction and magnitude of the angular impulse depend on the individual's ability to generate a moment about the COM within the afforded time [7,9]. When the GRF passes anterior to the COM, a backward moment is applied about the COM, thereby creating backward angular impulse. In contrast, when the GRF passes posterior to the COM, a forward moment is applied about the COM, creating forward angular impulse. The magnitude of the moment created by the GRF about the COM depends on the magnitude of the GRF and the orientation of the GRF relative to the COM. The longer the perpendicular distance (moment arm) is between the line of action of the GRF and the COM, the larger the moment generated by the GRF about the COM.

In standing, classic control strategies, such as the fixed support or feet-in-place hip and ankle preprogrammed strategies, have been proposed to maintain balance when the body is unexpectedly perturbed [10–11]. However, when the body is forcefully perturbed as in tripping, the fixed support ankle and hip strategies may not be sufficient for regaining balance. Consequently, compensatory responses to large perturbations often involve a stepping strategy to arrest the translation and rotation of the body.

A stepping strategy has been shown to be a "strategy of choice" even when younger and older adults experience smaller perturbations during bilateral stance [12]. Use of a stepping strategy for recovering balance requires coordination of both the support and swing legs. Previous research has emphasized the role of the swing leg to establish a larger base of support and reduce the linear momentum of the body after perturbation [12–17]. The swing leg has also been shown to be important in generating the angular impulse required to neutralize the angular momentum of the body induced by the perturbation [17]. The support leg has recently been found to help neutralize the angular momentum of the body early in the balance recovery phase [5,7,9,18]. In this article, we review the role of the swing and support legs in regulating angular impulse during fall recovery and contrast the balance recovery strategies used by younger adults and older adult nonfallers and fallers.

MECHANICS OF FORWARD FALL RECOVERY

A forward fall is commonly observed when the forward angular momentum of the body, induced by a backward slip or forward trip of the foot during forward gait, is not sufficiently neutralized during the balance recovery phase [5,7,9,15–18]. For example, during a forward trip, the backward-directed component of the GRF, acting on the tripping leg, passes posterior to the COM and contributes to the forward angular impulse about the COM (**Figure 1**). To recover from a forward trip, an individual must generate sufficient backward angular impulse during the balance recovery phase to neutralize the forward angular momentum of the body resulting from the trip [5,7,9]. An inability to neutralize the forward angular momentum of the body will result in a forward fall [5].

Role of Swing Leg During Forward Fall Recovery

Successful balance recovery by way of a stepping strategy uses angular impulse generated by the swing leg during both the swing and contact phases immediately following the perturbation. In the case of forward fall recovery resulting from a trip, the individual steps forward and the foot of the swing leg is placed anterior to the body, which causes a backward- and upward-directed GRF [17]. The horizontal component of the GRF acts as a braking force (posterior-directed) and slows the forward momentum of the body. Simultaneously, the resultant GRF passes anterior to the COM, creating backward angular impulse about the COM to neutralize the forward angular momentum of the body induced by the trip [5,7,9]. The magnitude of the moment created about the COM by the GRF depends on the magnitude of the resultant GRF, as well as the relative angle between the resultant GRF and the COM (the wider the angle, the longer the moment arm).

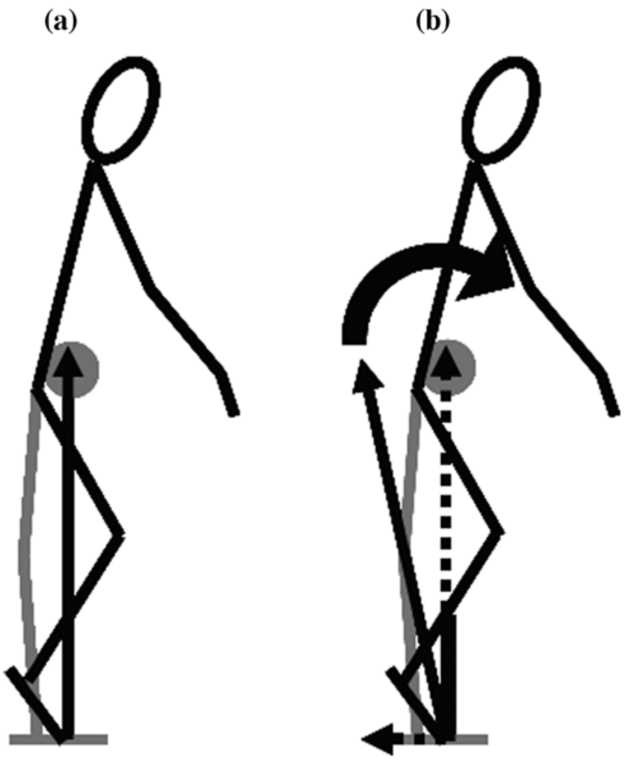

Figure 1.
Orientation of resultant ground reaction force (GRF) relative to total-body center of mass (COM) (solid gray circles) under normal and tripping conditions: **(a)** During midstance of normal gait, resultant GRF (solid arrow) acts toward COM. As result, no moment is created by GRF about COM, so no net angular impulse about COM is generated. In contrast, **(b)** during tripping, swing foot contacts with obstacle generating backward-directed GRF (dashed arrow) and resultant GRF (solid arrow) is directed posterior to COM. As result, forward moment by GRF about COM (curved arrow) is applied, increasing forward angular momentum of body.

Stepping strategies to regain balance after being released from forward-leaning positions differ between younger (aged 19–29) and older adults (aged 65–83) [13–17]. For example, older adults require a significantly smaller maximum forward lean angle before release to regain balance as compared with the younger adults [13–15]. The reported inability of older adults to successfully recover their balance using a stepping strategy when released from a relatively wide forward-lean angle was attributed to the longer reaction times [13–14], diminished lower-limb joint angular velocities during the swing phase [13–15], and insufficient control of the GRF applied to the stepping foot as compared with younger adults.

Swing Leg Mechanics During Swing Phase

The response execution speed of the swing leg during fall recovery has been shown to be associated with successful forward fall recovery [13–15]. The reaction time from the time of release in the forward-lean position to the time of swing leg foot liftoff was significantly longer for the older adults (aged 65–83) than the younger adults (aged 19–29) [13–14]. The peak hip and knee flexion velocities observed during the flexion phase following the liftoff of the swing leg were lower in older males than the younger males. Likewise, the peak knee and ankle extension velocities during the extension phase before the swing leg foot contact were lower in older males than the younger males [15]. When compared at the same forward lean angles, the older adults took multiple steps with shorter step lengths than the younger adults [14,16]. Likewise, older adults who failed to recover balance used shorter step lengths than those who successfully regained their balance [19].

These data suggest that the slower reaction times and lower-limb joint angular velocities observed in older adults may constrain step length [13–15]. As compared with longer step lengths, shorter step lengths are expected to reduce the magnitude of the backward-directed component of the GRF [20–21] applied to the swing leg during contact with the ground. Reducing the magnitude of the backward-directed component of the GRF reduces the horizontal velocity of the COM and the magnitude of the moment created by the GRF about the COM. As a result, the magnitude of linear and angular impulses generated by older adults during the first step of forward fall recovery is expected to be less than that of the younger adults. Inability to generate sufficient linear and angular impulses within the first step is consistent with the need for older adults to take multiple steps to recover balance. Use of a multiple step strategy to recover balance may be compromised by environmental constraints that limit the distance of travel and by an increased risk of colliding into other people or nearby objects. These results and the associated mechanics suggest that longer and fewer steps may provide a feasible option for fall recovery in a constrained environment if the individual can control the GRF applied during the swing foot contact. Developing a fall recovery strategy that increases the impulse generated for each step (e.g., increase step length) and reduces the required number of steps may be an effective compromise.

Swing Leg Mechanics During Contact Phase

After the swing leg foot contacts the ground, an individual regains balance by controlling the GRF relative to the COM [17]. Analysis of reported experimental data [17] indicates that the forward angular momentum associated with a forward fall is neutralized primarily during the impact phase, whereas the forward and downward linear momentum associated with a fall was reduced during the postimpact phase.

During the impact phase (initial 60–120 ms after swing foot contact), rapid changes in direction of the resultant GRF occur and cause an upward- and forward-directed GRF relative to the COM (**Figure 2(a)**) [17]. The upward component of the GRF retards the downward momentum of the COM. The forward component of the GRF increases the forward velocity of the COM and also creates a backward moment about the COM to neutralize the forward momentum.

During the postimpact phase of swing foot contact, the backward component of the GRF contributes to a decrease in the forward velocity of the COM. Approximately 120 ms postswing foot contact, the horizontal component of the GRF is redirected toward the posterior and slows down the forward velocity of the COM. During this interval, the GRF is essentially aligned with the COM [17] and results in minimal angular impulse generation (**Figure 2(b)**). These results indicate that the forward angular momentum associated with the forward fall was neutralized primarily during the impact phase, whereas the forward and downward translation of the COM associated with the fall was reduced during the postimpact phase. The pattern of GRF relative to the COM during the impact and postimpact phases was consistent between younger and older adults [17].

Successful regulation of angular and linear impulses during the impact and postimpact phases involves multijoint coordination of the lower limb [17]. During the impact phase, the knee and hip net joint moments (NJMs) of the swing leg oscillate with the change in direction of the resultant GRF. At the time of peak forward-directed GRF relative to the COM, hip extensor, knee flexor, and ankle plantar flexor NJMs were observed (**Figure 3(a)**) [17]. During the postimpact phase, ankle plantar flexor and knee and hip extensor NJMs (**Figure 3(b)**) were observed and fluctuated less than those observed in the impact phase [17]. In addition, the peak magnitudes of the knee and hip NJMs were significantly less during the postimpact phase as compared with those of the impact

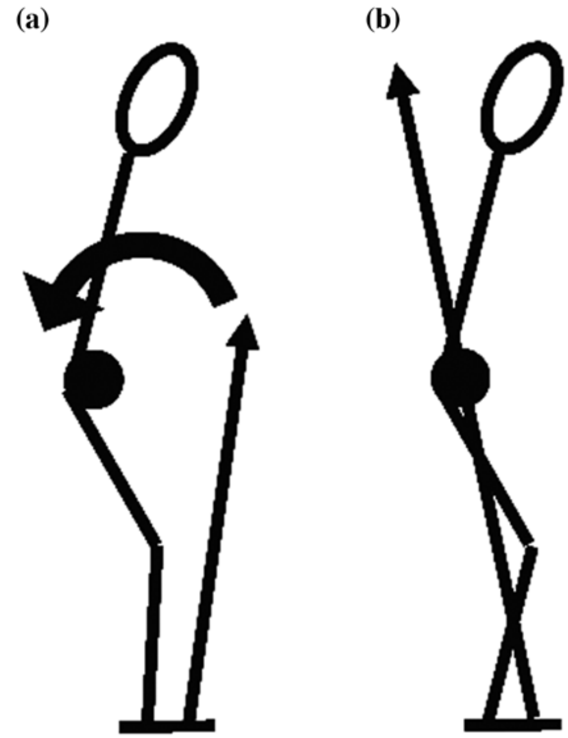

Figure 2.
Orientation of resultant ground reaction force (GRF) (straight arrow) relative to total-body center of mass (COM) (solid circle) and lower-limb segments: **(a)** At ~60 ms postswing leg contact, resultant GRF (straight arrow) is directed anterior to COM, generating backward moment about COM (curved arrow). This backward moment is applied over time, thereby generating backward angular impulse to neutralize forward angular momentum induced by trip. **(b)** At ~120 ms postswing leg contact, GRF (straight arrow) is acting toward COM, generating minimal angular impulse generation.

phase. The patterns of ankle, knee, and hip NJMs observed during the impact and postimpact phases of the swing leg contact were consistent between younger and older adults [17].

Between-phase differences in the lower-limb NJMs during the contact phase of the swing leg suggest control of the swing leg involves phase-specific muscle activation patterns. The patterns of swing leg NJMs observed during the swing leg contact phase were similar to those observed during the landing phase from a forward rotation jump [22] and running [23]. From these results, we hypothesized that during the impact phase, muscles crossing both sides of the knee and hip joints would be coactivated to control the rapid oscillation of the knee and hip NJMs to direct the GRF anterior to the COM

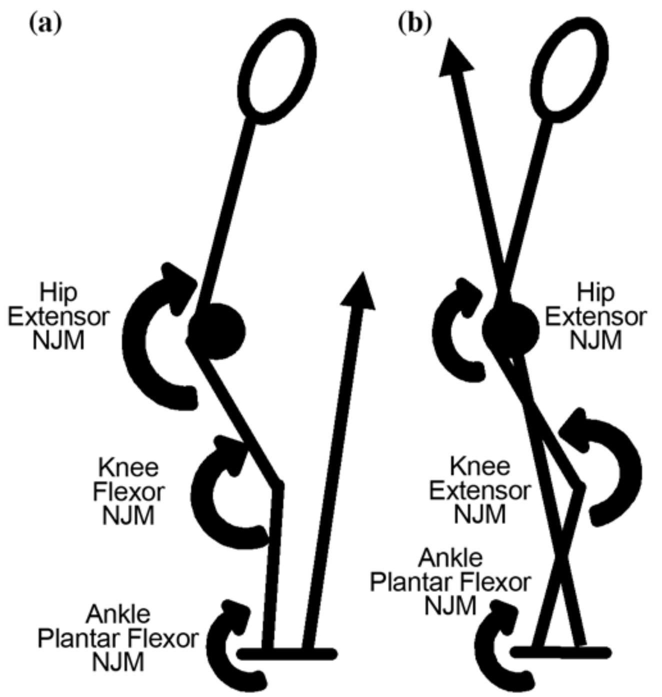

Figure 3.
Redirection of ground reaction force (GRF) requires coordination of lower-limb net joint moments (NJMs) (curved arrows): **(a)** During impact phase, set of ankle plantar flexor, knee flexor, and hip extensor NJMs is used to direct resultant GRF (straight arrow) anterior to center of mass (COM) (solid circle), thereby generating backward angular impulse (curved arrows). **(b)** During stabilization postimpact phase, set of ankle plantar flexor, knee extensor, and hip extensor NJMs is required to direct resultant GRF toward COM (straight arrow).

[18,22–23]. Muscle coactivation is thought to increase stiffness and stability of the lower limb during the impact phase [24]. At the knee joint, coactivation between the hamstrings and quadriceps femoris with hamstrings dominant may be observed to accommodate for the peak knee flexor NJMs [22]. Likewise, coactivation between gluteus maximus, hamstrings, and rectus femoris is expected to accommodate the peak hip extensor NJMs [22]. In contrast, during the postimpact phase, vasti and gluteus maximus dominant activation patterns are expected to direct the GRF more posterior toward the COM [18,22,25–28]. The phase-specific differences in NJMs and potentially their associated muscle activation patterns observed during the impact and postimpact phases of forward fall recovery suggest the need to investigate phase-specific training strategies for improving GRF control relative to the COM during the contact phase of the swing leg.

Although the patterns of GRF and NJMs were consistent between younger and older adults who successfully arrested the forward fall within one step, age differences in magnitude of lower-limb NJMs were observed [17]. During the impact phase, the peak hip extensor NJMs were greater in the older adults than in the younger adults. During the postimpact phase, the peak knee extensor NJMs were observed to be significantly smaller in older males than in younger males. No significant differences in hip and ankle NJMs were noted between the younger and older males [15,17]. The differences in knee extensor NJMs observed during the postimpact phase of forward fall recovery of the older and younger males may reflect the differences in the orientation of the GRF and the shank segment [25–26,28].

At the same relative step length used to arrest a forward fall, older females generated significantly lower ankle plantar flexor and hip extensor NJMs than younger females [15]. No significant difference in knee extensor NJMs was observed between the younger and older females. However, the mean magnitudes of lower-limb NJMs used by older females during forward fall recovery from a maximum forward lean equaled or exceeded assumed maxima in ankle plantar flexor, knee extensor and flexor, and hip extensor torques [15]. These results support the need to improve the ability of older females to generate lower-limb NJMs so that they have the muscle force needed to redirect the GRF relative to the COM as part of forward fall recovery.

Role of Support Leg During Forward Fall Recovery

Neutralization of the forward angular momentum by a reactive mechanism of the support leg has been shown to be an effective strategy for forward fall recovery. In these studies, younger adults (mean age 27 years) and older adult nonfallers (mean age 67 years) and fallers (mean age 68 years) were tripped during midswing phase of a gait cycle [5,7,9,18]. The researcher compared responses of the support leg at the total-body, lower-limb, and muscle levels during successful and unsuccessful forward fall recoveries [5,7,9,18]. In all trials with a forward trip, forward angular momentum of the body was generated by the posterior-directed GRF applied to the body at the foot-obstacle interface. In trials with successful forward fall recovery using a single step, younger adults and older adult nonfallers generated sufficient backward angular impulse to neutralize the forward angular

JRRD, Volume 45, Number 8, 2008

momentum of the body induced by the trip. Younger adults and older adult nonfallers were able to generate this backward angular impulse about the COM by the support leg with an increase in the upward and forward GRFs relative to the COM (**Figure 4(a)**) [9]. Neutralizing the forward angular momentum of the body induced by the trip, by generating backward angular impulse about the COM, enabled the individual to continue with normal gait. The increase in upward and forward components of the GRF during the fall recovery phase was associated with an increase in COM velocity in the upward and forward directions. Altering the COM trajectory allowed the swing leg sufficient time to initiate contact in a position feasible for maintaining gait [7,9]. During unsuccessful forward fall recovery, the older adult fallers were unable to neutralize the angular momentum of the body induced by the trip perturbation [5]. These results indicate that the older adult fallers did not generate sufficient backward angular impulse about the COM during the first step to neutralize the angular momentum of the body [5], thereby introducing the need to take multiple steps.

Successful fall recovery following a trip involves multijoint control of the support leg [5,7,9,18]. To counteract a forward fall, the ankle, knee, and hip work together to generate a GRF passing anterior to the COM to neutralize the forward angular momentum induced by the trip (**Figure 4(b)**) [9,18]. Both younger adults and older adult nonfallers are reported to use ankle plantar flexor, knee flexor, and hip extensor NJMs to redirect the GRF anterior to the COM in response to a trip. In contrast, older adult fallers who were unable to successfully recover from a forward trip using one step had significantly less ankle plantar flexor NJMs and slower rates of change in ankle, knee, and hip NJMs than younger adults and older adult nonfallers [5]. These results suggest that older adult fallers may be limited in their ability to generate sufficient magnitude ankle plantar flexor, knee flexor, and hip extensor NJMs in response to a trip. Although muscle strength of the older adult fallers was not measured in the study [5], the lower-limb muscular strength of older adult fallers was reported to be significantly less than older adult nonfallers [29–31]. Collectively, these results suggest that improvements in muscle strength and rate of muscle force development may give older adult fallers the muscular capacity to regulate angular impulse during the push-off phase.

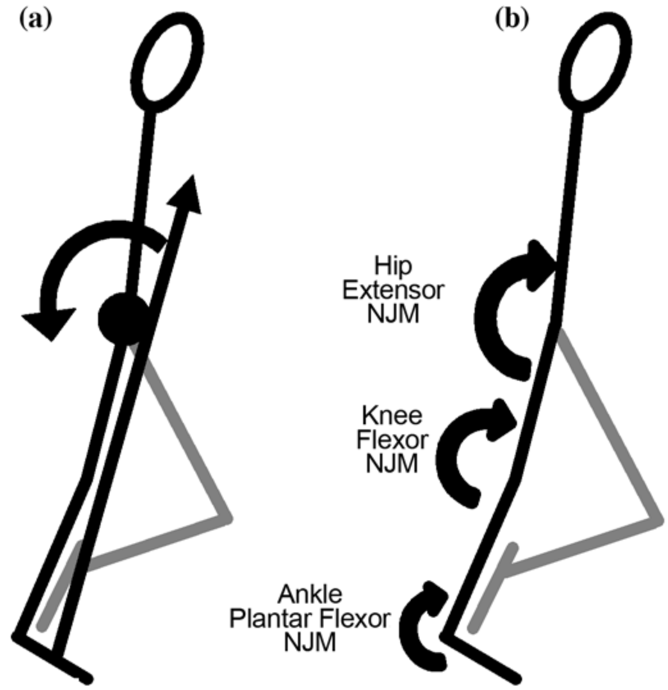

Figure 4.
(a) During forward fall recovery, support leg redirects resultant ground reaction force (GRF) (straight arrow) anterior to total-body center of mass (COM) (solid circle) to generate backward angular impulse and neutralize forward angular impulse (curved arrow) experienced during tripping. **(b)** Set of ankle plantar flexor, knee flexor, and hip extensor net joint moments (NJMs) (curved arrows) is used to redirect GRF anterior to total COM, generating backward angular impulse.

MECHANICS OF BACKWARD FALL RECOVERY

A fall is more likely to occur when an external perturbation induces backward rather than forward angular momentum [24–26]. In standing, nondisabled individuals are twice as likely to fall in a backward direction than in a forward and lateral direction when perturbed at a similar intensity [32–33]. Likewise, patients with Parkinson’s disease demonstrated a significant increase in postural instability during backward perturbations as compared with those in the forward and lateral directions [34]. An increase in postural instability in the backward direction is attributed in part to the limited ability to regulate the center of pressure in the posterior direction as compared with the anterior direction [35]. Experimental evidence indicates that deficits in center of pressure regulation were significantly more pronounced in the backward direction than other directions for older adults as compared with younger adults [36]. Inability to recover from a backward fall has been reported to result in a severe injury (i.e., hip fracture) in older adults [37]. Despite the likelihood of a backward fall and the severity of injury associated with the fall, little is known about the mechanics and neuromuscular control of backward fall recovery.

Backward falls are commonly observed when an external perturbation is applied in a backward direction at the shoulders [34] or hips [38] during forward translation of the surface [8,34] and during gait [38]. Backward postural instability can also be observed in older adults during functional activities involving single-leg stance with forward movements of the legs (i.e., getting dressed). To counteract the backward angular momentum induced by the perturbation, the body must generate forward angular impulse during interaction with the environment. Backward fall recovery has been achieved by using hip and ankle strategies and backward stepping strategies. Although a study reported that a stepping strategy was observed when the perturbation was relatively large [10], a more recent study reported that both younger and older adults favored (98% of the time) a backward stepping strategy over other fall recovery strategies to regain the balance, even when the perturbation was relatively small [12].

Role of Swing Leg During Backward Fall Recovery

As in forward fall recovery, age-related differences in backward stepping strategy are observed during backward fall recovery. In response to relatively large backward pull perturbations, younger adults (mean age 22 years) consistently used a single step to recover balance. In contrast, the majority of older adults (mean age 73 years) used multiple steps to recover from a backward pull. In addition, the steps taken by older adults occurred earlier after perturbation and were shorter in length than those of the younger adults [38]. Although the GRFs were not reported in this study [38], the shorter step lengths used by older adults would result in lower GRFs [20–21] compared with the longer step lengths used by the younger adults. If the contact durations were assumed to be similar between groups, the magnitude of the linear and angular impulses generated during the contact phase of the swing leg would also be less in older adults than in younger adults. As a result, older adults are likely to need more steps to recover from a relatively large backward pull than younger adults [38].

Successful recovery from a backward fall after being released from a backward-lean angle has been shown to be associated with the body configuration at the time of swing foot contact [39]. For example, older adults (mean age 75 years) released from a backward lean angle of 7° were instructed to recover with a single step [39]. Data from multiple release trials indicated that 50 percent of the older adults who successfully recovered from a backward fall used a single-step strategy, 27 percent used a multiple-step strategy, and 23 percent used a mixed- (single- and multiple-) step strategy. At the time of swing leg contact, the backward body lean angle was narrower in the older adults taking a single step than the angle in the older adults taking multiple steps. In addition, the stepping angle (angular displacement of the swing leg relative to the support leg) tended to be wider in the older adult taking single steps than that in the older adult taking multiple steps [39]. Larger angular displacement of the swing leg is likely associated with a longer step length. As in forward fall recovery, longer step lengths are associated with greater braking forces and angular impulse applied during contact to oppose the linear and angular momentum induced by the perturbation. These results explain, in part, how step length and body lean may contribute to different successful backward fall recovery strategies that older adults use.

Successful recovery from a backward fall also requires multijoint control of the lower limb. During the contact phase of the swing leg, ankle plantar flexor, knee extensor, and hip flexor NJMs (**Figure 5**) were observed in both single- and multiple-step strategies [39]. The NJM patterns observed during swing leg contact phase (ankle plantar flexor, knee extensor, and hip flexor) were similar to those tasks requiring forward angular impulse generation [22,25–26,40]. The peak magnitudes of the GRF and lower-limb NJMs were not significantly different between older adults taking a single step and those taking multiple steps [39]. These results suggest that during swing foot contact, forward angular and linear impulse generation was comparable between groups. The need for multiple steps may be associated with the degree of backward lean and potentially a greater magnitude of the COM velocity and angular momentum at swing leg foot contact. As a result, the forward angular and linear impulse generated during a single step may not be sufficient to neutralize the backward angular and linear angular

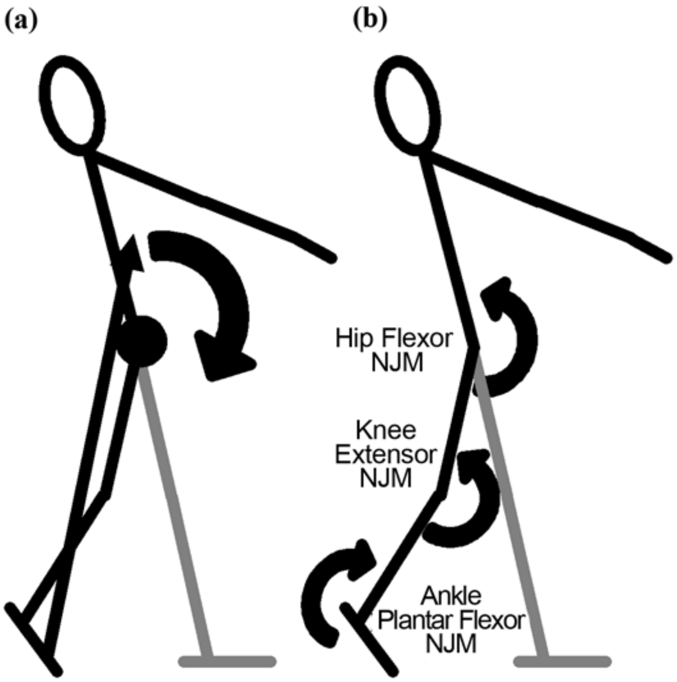

Figure 5.
(a) During backward fall recovery, swing leg redirects resultant ground reaction force (GRF) (straight arrow) posterior to total-body center of mass (COM) (solid circle) to generate forward angular impulse (curved arrow) to neutralize backward angular momentum induced by backward fall. **(b)** Set of ankle plantar flexor, knee extensor, and hip flexor net joint moments (NJMs) (curved arrows) is used to redirect resultant GRF (straight arrow) posterior to total-body COM during push phase so that forward angular impulse required to neutralize backward angular momentum of body can be generated.

momentum at contact, thereby creating the need for one to take multiple steps to recover from a backward fall.

Forward fall recovery and backward fall recovery strategies involve different multijoint control patterns. Lower-limb NJM patterns observed during the swing leg contact of the backward fall recovery were different from those observed during the forward fall recovery [5,39]. During the forward fall recovery, a set of ankle plantar flexor, knee flexor, and hip extensor NJMs was used for neutralizing the forward angular impulse during the impact phase [5]. In contrast, during the backward fall recovery, a set of ankle plantar flexor, knee extensor, and hip flexor NJMs were used [39]. The differences in the knee and hip NJMs observed between fall recovery conditions suggest that the muscle activation patterns needed for the body to successfully regain balance are task-specific. For example, during forward fall recovery, dominant activation of the gluteus maximus and hamstrings with coactivation of the vasti was observed [7,9]. However, during backward fall recovery, dominant activation of the hip flexor, rectus femoris, and vasti with coactivation of the hamstrings was expected [22,25–27].

Role of Support Leg During Backward Fall Recovery

Mechanisms used by the support leg to regulate forward angular impulse during backward fall recovery require further investigation. As observed during forward fall recovery [5,7,9], we hypothesize that the support leg could significantly contribute to backward fall recovery by redirecting the GRF relative to the COM. Generating a GRF posterior to the COM by the support leg would generate forward angular impulse required to neutralize the backward angular momentum generated during the perturbation [8]. As a result, the swing leg would need to generate less backward angular impulse [5,7,9], thereby creating a possibility of recovering balance within one step. As observed during forward fall recovery [5,7,18,27], regulating angular impulse would involve coordinating the ankle, knee, and hip NJMs and activating the corresponding lower-limb muscles [5,7,18,27]. These hypotheses based on the assimilation of existing data must be systematically investigated through further research.

Despite the lack of research investigation and understanding of the roles of the support leg on backward fall recovery, clinicians continue to face the need to provide therapy and educate the patients with backward falls. Understanding the regulation of backward angular impulse by generating forward angular impulse allows clinicians with basic knowledge to explore new therapy strategies to improve backward recovery. In a recent study, we investigated how forward angular impulse during backward translating tasks was generated in younger adults [40–42]. The mechanical objectives of this task were similar to those of the support leg during the backward fall recovery (forward angular impulse generation). We found that, at the total-body level, the subject generated the forward angular impulse during backward translating tasks by redirecting the GRF posterior to the COM (**Figure 6(a)**) [40]. At the lower-limb level, the subject used a set of knee extensor NJMs, relatively small hip extensor or flexor NJMs, and ankle plantar flexor NJMs to redirect the GRF posterior to the COM (**Figure 6(b)**) [40–42]. The differences between the knee and hip NJMs were a means to modulate the magnitude of the forward

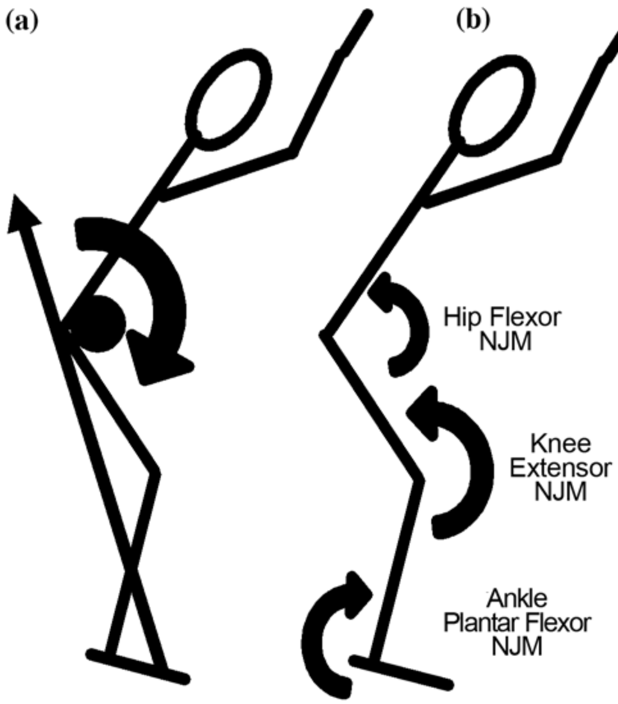

Figure 6.
(a) Generation of forward moment by resultant ground reaction force (GRF) about center of mass (COM) (solid circle) during push phase of inward somersault (curved arrow) requires that GRF be directed posterior to total-body COM. **(b)** Set of ankle plantar flexor, knee extensor, and hip flexor net joint moments (NJMs) (curved arrows) is used by skilled divers to direct resultant GRF relative to COM.

angular impulse. For example, to generate a relatively large forward angular impulse, the support leg needed to generate large knee extensor NJMs and hip flexor NJMs. In contrast, the support leg needed to generate relatively small knee extensor NJMs and large hip extensor NJMs to generate a relatively small forward angular impulse [40]. Activation of the rectus femoris and vasti and coactivation of hip flexor and extensors would be required during forward angular impulse generation [22,25–26]. Understanding how backward angular impulse is regulated provides an experimental context for exploring potential contributions by the support leg in backward fall recovery.

CONCLUSIONS

Regulation of angular impulse, by stepping strategies, is an essential part of fall recovery. Multijoint control of the swing and support legs is important in regulating the magnitude and direction of the angular impulse generated about the COM. Execution of a successful stepping strategy with the swing leg, as observed in younger adults, requires (1) a relatively short reaction time to initiate the recovery movement following the perturbation, (2) fast flexion and extension velocities of lower-limb joints during the swing phase to position the foot anterior to the COM, (3) a long step length to create a large base of support, and (4) coordinated and sufficient lower-limb NJMs to regulate angular impulse. In contrast, older adults demonstrate (1) relatively long reaction times, (2) slow flexion and extension velocities of lower-limb joints of the swing leg, (3) a short step length and base of support relative to the COM, and (4) reduced lower-limb NJMs to regulate angular impulse during the contact phase of the swing leg.

For the support leg, the inability to sufficiently redirect the GRF relative to the COM observed in older adult fallers is attributed to their inability to redistribute the lower-limb NJMs to regulate the angular impulse. An individual can generate needed backward angular impulse for a forward fall recovery by generating a set of relatively large hip extensor NJMs and small knee extensor or knee flexor NJMs by activating the gluteus maximus and hamstrings. In contrast, an individual can generate the forward angular impulse required for backward fall recovery by generating a set of relatively large knee extensor NJMs and small hip extensor or flexor NJMs by activating rectus femoris and monoarticular hip flexor, vasti, and gluteus maximus. Improving the swing phase mechanics of the swing leg by increasing lower-limb joint flexion and extension velocities may provide older adults an opportunity to increase step length during fall recovery. Enhancing the contact phase mechanics of the swing and support legs by strengthening and coordinating the lower-limb muscles specific to the direction of angular impulse requirements may be an effective means for older adults to prepare for fall recovery.

ACKNOWLEDGMENTS

This material was based on work supported in part by training grant 5T32AG000930 in Neurobiology and Endocrinology of Aging, Andrus Gerontology Center, University of Southern California.

The authors have declared that no competing interests exist.

REFERENCES

1. Perry J. Gait analysis: Normal and pathological function. Thorofare (NJ): Slack; 1992.
2. Winter DA. Overall principle of lower limb support during stance phase of gait. J Biomech. 1980;13(11):923–27. [PMID: 7275999]
3. MacKinnon CD, Winter DA. Control of whole body balance in the frontal plane during human walking. J Biomech. 1993;26(6):633–44. [PMID: 8514809]
4. Patla AE, Prentice SD, Robinson C, Neufeld J. Visual control of locomotion: strategies for changing direction and for going over obstacles. J Exp Psychol Hum Percept Perform. 1991;17(3):603–34. [PMID: 1834781]
5. Pijnappels M, Bobbert MF, Van Dieën JH. Push-off reactions in recovery after tripping discriminate young subjects, older non-fallers and older fallers. Gait Posture. 2005; 21(4):388–94. [PMID: 15886128]
6. Stack E, Ashburn A. Fall events described by people with Parkinson's disease: implications for clinical interviewing and the research agenda. Physiother Res Int. 1999;4(3): 190–200. [PMID: 10581625]
7. Pijnappels M, Bobbert MF, Van Dieën JH. Contribution of the support limb in control of angular momentum after tripping. J Biomech. 2004;37(12):1811–18. [PMID: 15519588]
8. Gu MJ, Schultz AB, Shepard NT, Alexander NB. Postural control in young and elderly adults when stance is perturbed: dynamics. J Biomech. 1996;29(3):319–29. [PMID: 8850638]
9. Pijnappels M, Bobbert MF, Van Dieën JH. How early reactions in the support limb contribute to balance recovery after tripping. J Biomech. 2005;38(3):627–34. [PMID: 15652564]
10. Horak FB, Nashner LM. Central programming of postural movements: adaptation to altered support-surface configurations. J Neurophysiol. 1986;55(6):1369–81. [PMID: 3734861]
11. Horak FB, Nashner LM, Diener HC. Postural strategies associated with somatosensory and vestibular loss. Exp Brain Res. 1990;82(1):167–77. [PMID: 2257901]
12. McIlroy WE, Maki BE. Age-related changes in compensatory stepping in response to unpredictable perturbations. J Gerontol A Biol Sci Med Sci. 1996;51(6):M289–96. [PMID: 8914501]
13. Thelen DG, Wojcik LA, Schultz AB, Ashton-Miller JA, Alexander NB. Age differences in using a rapid step to regain balance during a forward fall. J Gerontol A Biol Sci Med Sci. 1997;52(1):M8–13. [PMID: 9008663]
14. Thelen DG, Muriuki M, James J, Schultz AB, Ashton-Miller JA, Alexander NB. Muscle activities used by young and old adults when stepping to regain balance during a forward fall. J Electromyogr Kinesiol. 2000;10(2):93–101. [PMID: 10699557]
15. Wojcik LA, Thelen DG, Schultz AB, Ashton-Miller JA, Alexander NB. Age and gender differences in single-step recovery from a forward fall. J Gerontol A Biol Sci Med Sci. 1999;54(1):M44–50. [PMID: 10026662]
16. Madigan ML, Lloyd EM. Age and stepping limb performance differences during a single-step recovery from a forward fall. J Gerontol A Biol Sci Med Sci. 2005;60(4):481–85. [PMID: 15933388]
17. Madigan ML, Lloyd EM. Age-related differences in peak joint torques during the support phase of single-step recovery from a forward fall. J Gerontol A Biol Sci Med Sci. 2005; 60(7):910–14. [PMID: 16079216]
18. Pijnappels M, Bobbert MF, Van Dieën JH. Control of support limb muscles in recovery after tripping in young and older subjects. Exp Brain Res. 2005;160(3):326–33. [PMID: 15322782]
19. Owings TM, Pavol MJ, Grabiner MD. Mechanisms of failed recovery following postural perturbations on a motorized treadmill mimic those associated with an actual forward trip. Clin Biomech (Bristol, Avon). 2001;16(9): 813–19. [PMID: 11714559]
20. Roberts TJ, Scales JA. Mechanical power output during running accelerations in wild turkeys. J Exp Biol. 2002; 205(Pt 10):1485–94. [PMID: 11976359]
21. Seyfarth A, Blickhan R, Van Leeuwen JL. Optimum takeoff techniques and muscle design for long jump. J Exp Biol. 2000;203(Pt 4):741–50. [PMID: 10648215]
22. McNitt-Gray JL, Hester DM, Mathiyakom W, Munkasy BA. Mechanical demand and multijoint control during landing depend on orientation of the body segments relative to the reaction force. J Biomech. 2001;34(11):1471–82. [PMID: 11672722]
23. Elliott BC, Blanksby BA. The synchronization of muscle activity and body segment movements during a running cycle. Med Sci Sports. 1979;11(4):322–27. [PMID: 530022]
24. Hogan N. Adaptive control of mechanical impedance by coactivation of antagonist muscles. IEEE Trans Automat Contr. 1984;29(8):681–90.
25. Mathiyakom W, McNitt-Gray JL, Wilcox R. Lower extremity control and dynamics during backward angular impulse generation in forward translating tasks. J Biomech. 2006; 39(6):990–1000. [PMID: 15878165]
26. Mathiyakom W, McNitt-Gray JL, Wilcox R. Lower extremity control and dynamics during backward angular impulse generation in backward translating tasks. Exp Brain Res. 2006;169(3):377–88. [PMID: 16273396]

27. Wells R, Evans N. Functions and recruitment patterns of one- and two-joint muscles under isometric and walking conditions. Hum Mov Sci. 1987;6(4):349–72.
28. Mathiyakom W, McNitt-Gray JL, Requejo P, Costa K. Modifying center of mass trajectory during sit-to-stand tasks redistributes the mechanical demand across the lower extremity joints. Clin Biomech (Bristol, Avon). 2005;20(1):105–11. [PMID: 15567544]
29. Daubney ME, Culham EG. Lower-extremity muscle force and balance performance in adults aged 65 years and older. Phys Ther. 1999;79(12):1177–85. [PMID: 10630286]
30. Takeuchi Y, Tanaka Y, Shimomura Y, Iwanaga K, Katsuura T. The effect of aging on the backward stepping reaction as estimated from the velocity of center of foot pressure and muscular strength. J Physiol Anthropol. 2007;26(2):185–89. [PMID: 17435363]
31. Johnson ME, Mille ML, Martinez KM, Crombie G, Rogers MW. Age-related changes in hip abductor and adductor joint torques. Arch Phys Med Rehabil. 2004;85(4):593–97. [PMID: 15083435]
32. Hsiao-Wecksler ET, Robinovitch SN. The effect of step length on young and elderly women's ability to recover balance. Clin Biomech (Bristol, Avon). 2007;22(5):574–80. [PMID: 17391819]
33. Hsiao ET, Robinovitch SN. Common protective movements govern unexpected falls from standing height. J Biomech. 1998;31(1):1–9. [PMID: 9596532]
34. Horak FB, Dimitrova D, Nutt JG. Direction-specific postural instability in subjects with Parkinson's disease. Exp Neurol. 2005;193(2):504–21. [PMID: 15869953]
35. Winter DA, Prince F, Frank JS, Powell C, Zabjek KF. Unified theory regarding A/P and M/L balance in quiet stance. J Neurophysiol. 1996;75(6):2334–43. [PMID: 8793746]
36. Fujiwara K, Ikegami H, Okada M, Koyoma Y. [Contribution of age and muscle strength of lower limbs to steadiness and stability in standing posture]. J Anthrop Soc. 1982;90:385–400. Japanese.
37. Sandler R, Robinovitch S. An analysis of the effect of lower extremity strength on impact severity during a backward fall. J Biomech Eng. 2001;123(6)590–98. [PMID: 11783730]
38. Luchies CW, Alexander NB, Schultz AB, Ashton-Miller J. Stepping responses of young and old adults to postural disturbances: kinematics. J Am Geriatr Soc. 1994;42(5):506–12. [PMID: 8176145]
39. Hsiao ET, Robinovitch SN. Elderly subjects' ability to recover balance with a single backward step associates with body configuration at step contact. J Gerontol A Biol Sci Med Sci. 2001;56(1):M42–47. [PMID: 11193232]
40. Mathiyakom W, McNitt-Gray JL, Wilcox R. Regulation of forward angular impulse in tasks with backward translation. Exp Brain Res. Forthcoming 2009.
41. Mathiyakom W, McNitt-Gray JL, Munkasy BA, Eagle J, Gabriel J. Joint kinetics differences during the inward and reverse diving takeoffs. Paper presented at: Proceedings of the XVIIth Congress of the International Society of Biomechanics; 1999 Aug; Calagary, AB, Canada. p. 167.
42. Mathiyakom W, McNitt-Gray JL. Generation of forward angular impulse in tasks with backward translation is achieved by redirecting the reaction force relative to the center of mass. Poster presented at: Proceedings of the XXth Congress of the International Society of Biomechanics; 2005 Aug; Cleveland, OH.

Submitted for publication February 28, 2008. Accepted in revised form October 15, 2008.