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Review Article

Understanding the Biomechanical Factors Related to Successful Balance Recovery and Falls: A Literature Review

Junwoo Park, PT, BPT, Jongwon Choi, PT, BPT, Woochol Joseph Choi, PT, PhD

Injury Prevention and Biomechanics Laboratory, Department of Physical Therapy, Yonsei University, Wonju, Korea

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Corresponding Author
Woochol Joseph Choi
E-mail: wcjchoi@yonsei.ac.kr
https://orcid.org/0000-0002-6623-3806

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Background: Despite fall prevention strategies suggested by researchers, falls are still a major health concern in older adults. Understanding factors that differentiate successful versus unsuccessful balance recovery may help improve the prevention strategies.

Objects: The purpose of this review was to identify biomechanical factors that differentiate successful versus unsuccessful balance recovery in the event of a fall.

Methods: The literature was searched through Google Scholar and PubMed. The following keywords were used: 'falls,' 'protective response,' 'protective strategy,' 'automated postural response,' 'slips,' 'trips,' 'stepping strategy,' 'muscle activity,' 'balance recovery,' 'successful balance recovery,' and 'failed balance recovery.'

Results: A total of 64 articles were found and reviewed. Most of studies included in this review suggested that kinematics during a fall was important to recover balance successfully. To be successful, appropriate movements were required, which governed by several things depending on the direction and characteristics of the fall. Studies also suggested that lower limb muscle activity and joint moments were important for successful balance recovery. Other factors associated with successful balance recovery included fall direction, age, appropriate protective strategy, overall health, comorbidity, gait speed, sex and anticipation of the fall.

Conclusion: This review discusses biomechanical factors related to successful versus unsuccessful balance recovery to help understand falls. Our review should help guide future research, or improve prevention strategies in the area of fall and injuries in older adults.

INTRODUCTION

Falls are a major health concern in older adults. One-quarter of older adults fall annually, and falls are the leading cause of death from unintentional injuries [1]. According to the Centers for Disease Control and Prevention (CDC), 2.8 million patients were treated for fall-related injuries in 2014 in the emergency room, and about 1 million of these patients were hospitalized [2]. Although many fall prevention strategies (i.e., exercise programs) have been developed and implemented, it is predicted that by 2030 falls will cause seven deaths per hour [1,3]. This may suggest that the current fall prevention strategies are ineffective, and a better understanding of factors that differentiate successful versus unsuccessful balance recovery may help improve the effectiveness of fall prevention strategies.

Fortunately, numerous research studies have examined these factors. Qu et al. [4] have found that successful balance recovery is determined by muscle activity of the lower limbs. Fatigue [5,6] and upper limb movements have also been associated with falls and balance recovery [7-9]. Furthermore, several other factors have been considered potential factors, including fall direction, age, appropriate protective strategy, lower limb kinematics, overall health and comorbidity, body configuration, gait speed, sex, anticipation of the fall, and kinetics of the lower limbs.

The purpose of this review was to identify factors that differentiate successful versus unsuccessful balance recovery in the event of a fall, categorizing into four biomechanical perspectives: kinematics, muscle activity, kinetics, and others.

MATERIALS AND METHODS

The literature published between 1993 and 2022 was obtained through a comprehensive search of databases (Google Scholar and PubMed) using the following keywords: falls, protective response, protective strategy, automated postural response, slips, trips, stepping strategy, muscle activity, balance recovery, successful balance recovery, and failed balance recovery. The search resulted in 138 articles. However, after excluding review articles, articles in which the original texts were not provided, and articles that were not indexed in the Journal Citation Report, a total of 64 articles were found and reviewed.

RESULTS

1. Kinematics

Body movements during a fall event were associated with balance recovery. A total of thirty-two studies have suggested that limb and trunk movements, stepping, and body configuration (i.e., trunk flexion angle and angle of lower body) are significantly associated with successful balance recovery [8-39]. Furthermore, twenty-one studies have suggested that lower limb movements, including step length, lower limb joint angles, and the presence of multiple steps, are significantly associated with successful balance recovery [8-13,16-21,24,25,27,29,31,32,37-39]. Upper limb movements and body configuration have also been found to be significantly associated with successful balance recovery in seventeen studies [8,9,11,18,20-26,30,31,33-36].

Twelve studies have examined body movements during a forward fall (trip) [8,11,17,19,20,22,24,30,33-35,39], six studies during a sideways fall [16,23,29,31,32,37], and seven studies during a backward fall (slips) [9,12-14,18,22,27]. Furthermore, four studies have examined body movements during different falling directions combined with various types of perturbations [10,26,36,38].

To simulate falls, various perturbation methods (i.e., slippery surface and linear motor) were used in sixteen studies [8-14,16,18,23,28,29,32,36-38], tether-release methods in seven studies [17,19-22,24,34], and obstacle methods in four studies [30,33,35,39]. In the tether-release method, a person was caused to fall by using a harness connected to a tether, which released unexpectedly, whereas the perturbation method used a slippery surface or perturbation motors. Two studies have used the obstacle method to mimic trip falls, in which a person was caused to fall by the obstacle on walkway [40,41].

2. Muscle Activity

Seventeen studies have suggested that muscle activity is significantly associated with successful balance recovery [4,19,26,40-53], where all but one study (which focused on the upper limb and trunk and lower limb muscle activity) [42] examined the lower limb muscle activity.

Nine studies have examined muscle activity during a forward fall [19,40,41,46-51], five studies during a backward fall [4,42-45], and one study during a sideways fall [53], whereas other studies examined muscle activity in several fall directions [26,52]. To simulate fall events, nine studies have used the tether-release method [19,42,46-52], and five studies the perturbation method [4,43-45,53].

3. Kinetics

Seven studies have suggested that joint moments in the event of a fall are significantly associated with successful balance recovery [13,20,27,31,40,54,55]. All of these studies have suggested that the joint moments of the lower limb and trunk, including the hip and knee extension moments, are significantly associated with successful balance recovery. Four studies have examined joint moments during a forward fall [20,40,54,55], two studies during a backward fall [13,27], and one study during a sideways fall [31].

4. Others

Seventeen studies have suggested that individuals' age and comorbidity are significantly associated with successful balance recovery [16,21,26,28,47,56-67]. Furthermore, the following elements have been suggested as risk factors, including physical and mental fatigue, anticipation, gait speed, fall direction, protective strategy [5-7,15,62,68-71].

DISCUSSION

The purpose of this review was to summarize and discuss biomechanical factors that differentiate successful versus unsuccessful balance recovery in the event of a fall from various perspectives.

1. Kinematics

Most of studies included in this review suggested that kinematics during a fall was important to recover balance successfully. To be successful, appropriate movements were required, which governed by several things depending on the direction and characteristics of the fall.

1) Kinematics during a forward fall

During a forward fall, a greater recovery step along with faster reaction time were helpful to recover balance [10,11,17,19,20]. The fast and large step quickly positions the center of mass posteriorly, creating the greater braking torque to stop the forward angular momentum. Ochi et al. [19] have found that elderly females with a history of falls have smaller recovery steps and slower stepping responses than those without. Hsiao-Wecksler and Robinovitch [17] have also suggested that a larger and quicker recovery step increases the ability to recover balance in females of all ages. Furthermore, the trunk flexion angle from the vertical at foot contact was a biomarker of successful balance recovery (the greater the angle, the greater the risk of a fall) [11,20,72]. Movements of upper limbs were also important to recover balance in the event of a fall [8,30,33-35] as the movements decreased body's angular momentum [30,35]. However, the benefits were compromised when a fall initiated with a greater trunk lean angle [34].

2) Kinematics during a backward fall

During a backward fall while walking forward, the kinematics of the slipping leg (i.e., smaller heel-strike angle and smaller displacement and average velocity of the slipping leg) was important to recover balance [12-14]. Short steps after a slip increased the likelihood of recovery. Furthermore, the slipping foot displacement exceeding 10 cm and velocity exceeding 50 cm/s increased fall risk as they may delay stepping responses, possibly resulting in a fall [12]. Furthermore, the kinematics of the arms and the trailing limb were also important to recover balance [9] as the arms assisted in shifting the center of mass anteriorly, and the trailing limb assisted in widening the base of support and increasing stability at loss of balance. Moreover, some studies have suggested that an increased trunk flexion along with a large backward step increase the probability of successful balance recovery during a backward fall [18,22].

3) Kinematics during a sideways fall

During a sideways fall, stepping strategies were important to recover balance [16,29,31,32,37]. In balance recovery, older adults were found to use more steps, arm movements, and grasping strategies than young adults [16]. This tendency might be due to fear of falling and declined static and dynamic balance. When compared to non-fallers, frequent fallers had compromised stepping responses at loss of balance [29] and exhibited greater step length with decreased reaction times. Furthermore, the presence of multiple steps was considered the strongest predictor of fall risk [31].

2. Muscle Activity

All of studies included in this review suggested that lower limb muscle activity was important for successful balance recovery.

1) Muscle activity during a forward fall

During a forward fall, lower limb muscle activity was important to recover balance [40,41,46-52]. Pijnappels et al. [40,41] have suggested that quick and large contractions of the hip extension and ankle plantarflexion muscles are required to stop forward rotation after tripping, and resistance training of the lower limb muscles is helpful to improve ability to recover balance. Furthermore, Karamanidis et al. [47] have suggested that the quadriceps and triceps surae muscle strengths are important to elicit the minimal step length required for successful balance recovery. Moreover, quite large muscle activity of the hip abductor muscles of the stance leg has been observed after tripping, suggesting that the hip abductor muscle strength is critical to recover balance after tripping [46,73,74].

Muscle activity patterns differed between young and older adults. Mackey and Robinovitch [49] have found that onset time of the tibialis anterior and soleus muscles is 26.6% smaller in young than older adults. Thelen et al. [50] have found that older adults exhibit prolonged muscle activity of the soleus, gastrocnemius, and biceps femoris in the stance leg during a forward fall. Furthermore, the activation of the vastus lateralis and deactivation of the rectus femoris in the stepping leg were delayed in older adults. Given the declined ability to recover balance in older adults, the muscle activation pattern (onset, intensity, and timing) seemed to be important for balance recovery.

2) Muscle activity during a backward fall

Similar to the forward fall, the muscle activity was important to recover balance during a backward fall [4,42-45]. Ding and Yang [45] have found that fallers exhibit significantly lower knee flexion and extension strength compared to non-fallers. In terms of onset time, the muscles (bilateral sternocleidomastoid, anterior and posterior deltoids, rectus abdominis, rectus femoris, and tibialis anterior) activated earlier in balance recovery with greater magnitude, suggesting that non-fallers respond faster to the loss of balance [44]. Furthermore, Chambers and Cham [43] have found that young adults exhibit longer and more powerful muscle contraction than older adults. Moreover, knee flexors were activated more quickly than knee extensors in young adults.

3) Muscle activity during a sideways fall

Similar to the forward and backward falls, the muscle activity was important to recover balance during a sideways fall. In particular, the hip abductor muscles were important as they govern stepping responses at imbalance. Addison et al. [53] have found that older adults who primarily used an initial medial step for balance recovery exhibit declined hip abductors compared to those who used a cross-step. Furthermore, multiple steps were required for balance recovery than those who used a cross-step. Finally, older non-fallers were found to use cross-steps, whereas older fallers used medial steps [75,76].

3. Kinetics

All of studies included in this review suggested that lower limb joint moments were important to recover balance.

1) Kinetics of forward, backward and sideways falls

Pijnappels et al. [40] have found that during a forward fall, the knee flexion, ankle plantar flexion, and hip extension moments of the support limb are critical to recover balance. These moments generated necessary push-off reaction and restrained forward angular momentum. Carty et al. [20] have suggested that the peak knee extension moments during the landing phase (the time when the knee flexion angle is the maximum after fall) has the strongest relationship with first-step stability. The rate of torque development of knee flexor muscles in non-fallers was also found to be greater than that of fallers [55]. Collectively, fast and greater torque generation during a fall was crucial to recover balance. During a backward fall, increased knee flexion and hip extension moments were shown to improve balance recovery [13]. Furthermore, hip abduction torque was identified as a significant variable for fall prediction during a sideways fall [31].

4. Others

Studies have suggested that comorbidity affects successful balance recovery. Handelzalts et al. [57] have found that patients who experienced a stroke exhibit more recovery steps than healthy older adults under the same perturbation magnitude. Furthermore, these patients tended to fall toward the paralyzed side with smaller perturbation intensity, compared to the control group. Hiller et al. [56] have found that young adults with functional ankle instabilities exhibit longer time to recover balance than healthy young adults.

Studies have also suggested that age influences successful balance recovery [16,21,26,28,47,61-67]. Using tether-release experiments, researchers have found that differences exist between older and young adults in muscle activity, peak joint velocity, step length, the number of recovery steps, lower limb joint torque, and maximum lean angle. Older adults exhibited slower gluteus medius onset time, smaller lower limb joint torque, slower peak joint velocity, more recovery steps and smaller maximum lean angle during tether release experiment than young adults.

Successful balance recovery was also affected by mental and physical fatigue [5,6]. Qu et al. [5] have found that participants in the mental fatigue group exhibit smaller recovery step length and larger trunk flexion angle after tripping than those in the control group, and lower limb physical fatigue is found to affect balance recovery.

Studies have also found that anticipation of a fall or experience of a fall affects successful balance recovery as it changes reaction time or postural response in the event of a fall [5,69,71]. Hsiao and Robinovitch [15] have also found that the fall direction is associated with successful balance recovery, and backward falls are found to occur most commonly during daily activities, whereas others have found that forward falls are most common in older adults [77].

CONCLUSIONS

We reviewed and discussed biomechanical factors related to successful versus unsuccessful balance recovery to help understand falls. Our review should help guide future research, or improve prevention strategies in the area of fall and injuries in older adults.

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CONFLICTS OF INTEREST

No potential conflicts of interest relevant to this article was reported.

AUTHOR CONTRIBUTIONS

Conceptualization: JP, WJC. Data curation: JP, JC, WJC. Formal analysis: JP, WJC. Funding acquisition: WJC. Investigation: JP, WJC. Methodology: JP, WJC. Project administration: JP, WJC. Resources: JP, WJC. Software: JP, WJC. Supervision: JP, WJC. Validation: JP, WJC. Visualization: JP, WJC. Writing – original draft: JP, WJC. Writing – review & editing: JP, WJC.

ORCID

Junwoo Park, https://orcid.org/0000-0003-4039-1782
Jongwon Choi, https://orcid.org/0000-0001-9207-5322

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