TEACHING OLDER ADULTS HOW TO FALL SAFELY

BY

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DISSERTATION

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ABSTRACT

Despite decades of scientific scrutiny on fall prevention, falls are still common and potentially disastrous. A novel approach that could augment current procedures is to teach older adults movement strategies to fall safely. The purpose of the current study was to determine whether older adults can learn a safe falling-strategy (“tuck-and-roll”) to reduce the risk of fall-related injuries. Consistent with the principles of motor learning, learning was quantified with changes in impact severity parameters following training (aim 1), transfer of the falling strategy to the untrained side (aim 2) and 1-week retention (aim 3). 17 healthy older individuals participated (age: 64.3±4.4 years, 14 males). Participants were randomly assigned into either training group (n=9) or active control group (n=8). All participants performed standardized sideways falls for baseline, post-test and 1-week retention test. During the falling assessments, kinetic and kinematic impact severity parameters were measured. The results for short-term learning revealed that while both groups showed significant reduction of impact severity at post-test compared to the baseline, the training group showed greater reduction than the control group. Also, there was no significant difference in impact severity between trained-side and untrained-side falls suggesting there was bilateral transfer effect. The 1-week retention test revealed that there was partial retention effect of the training. Collectively, we conclude that the reduction of impact severity measurements in the training group might be due to effectiveness of the tuck-and-roll strategy. Furthermore, the participants were able to bilaterally transfer and partially retain the effectiveness of the training. However, the current study also observed potential risks of the tuck-and-roll strategy, such as head impact, when the strategy was not performed properly. Given the promising results of the current study, developing a comprehensive training program to teach safe landing strategy for older adults maybe an important step for fall related injury prevention.
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CHAPTER 1: INTRODUCTION

1.1. Falls in older people

Falls are the leading causes of accidental injury and death among the elderly [1]. An estimated 40% of community-dwelling people aged over 65 years fall at least once a year, and nearly 15% fall twice or more per year [2]. Falls result in 62.5% (2.5 million) of non-fatal injuries of older adults in the United States that require treatment in emergency departments and hospitalization [3]. The direct medical cost for fall-related injuries reaches $19 billion annually in the U.S. [4]. Giving the greying of America, the number of annual fall related injuries in the United States is expected to increase to 5.7 million by the year 2030 [5]. Indeed, 90% of hip fractures in older adults result from falls [6]. Falls not only lead to physical injuries but they also lead to activity curtailment, physiological deconditioning and reduction in quality of life [4]. Given the frequency and severity of falls they have been the topic of scientific scrutiny for decades [7].

1.2. Fall preventions in older people

Injury prevention efforts have mainly targeted intrinsic (e.g., physical or cognitive abilities) or extrinsic (e.g., physical or social environment) fall risk factors [8]. For example, fall prevention programs often consist of recommendations on environmental modification (e.g., improving lighting, installing handrails), behavioral education (e.g., not hurried while walking, using mobility device), and exercise training (e.g., muscle strengthening, tai-chi) [9]. Especially, exercise interventions are one of the most efficient approaches to reduce fall risk, as it can significantly improve physiological capacity for balance and reduced monthly rate of falling in older adults [9].
A meta-analysis study incorporating 22 studies (4912 participants) demonstrated that exercise significantly reduced falls ranging from 13%-61% in the rate of falls [10]. However, it is important to note that despite the benefits of targeted exercise training, participants within these programs still fall [7, 8].

1.3. Effect of a safe landing strategy

An alternative approach is to teach individuals how to fall safely in such a manner to reduce injury. It has been demonstrated that there are unique protective movements which reduce the risk of injury during a fall [11]. A recent systematic review paper provided quantitative evidences indicating that safe-landing strategies can significantly reduce the risk of injury from falling [12] (Appendix A). The risk of injury has been quantified by various biomechanical parameters (e.g., force, velocity) that reflect magnitude of loads applied to the body at impact (i.e., impact severity). Also, the types of strategies are based on the falling direction and the part of body being protected. The review paper found a total of 7 landing strategies (backward fall: squatting; forward fall: elbow flexion; sideway fall: forward rotation, tuck-and-rolling, hand slapping on the ground, relaxed muscle, and stepping) in 13 investigations encompassing 219 individuals. In general, all strategies, except for the hand slapping technique, significantly reduce impact severity on hip or wrist by 12% to 44% (Figure 1).

Especially, given that falling to the side has 6-fold greater risk for hip fracture than forward or backward falls, 69% of investigations (9 out of 13 studies) focused on sideway falls [6]. Among the side way fall strategies, the tuck-and-roll technique demonstrated the greatest efficiency on reducing impact severity on the hip in diverse biomechanical parameters (hip impact force: 25% reduction; hip impact velocity: 11% reduction) [12]. The tuck-and-roll technique is characterized
by knee flexion, lateral trunk flexion, and rotation backward during descent to change a fall into rolling after an impact (Figure 2) [13]. By rolling, the forces are distributed over a larger impact site and the amount of energy to be absorbed during impact is reduced because kinetic energy is preserved during the rolling movement [13]. Additionally, the tuck-and-roll strategy changes the body configuration at landing, resulting in a reduced vertical angle of the trunk relative to the floor at impact which leads to less energy absorbed by hip by 22% [14]. Given the fact that the tuck-and-roll was reported to be the most effective strategy to reduce impact severity in sideways falling, current project will focus on training the strategy.

1.4. Limitation of previous research

Despite the promise of teaching safe-landing strategies, previous investigations had several limitations. 87% of participants in the investigations were young, healthy subjects (average age: 28+/-13.2 years). It has been speculated that elderly individuals might have diminished ability to perform the safe landing strategy because of reduced muscle strength, belated detection of imbalance and delayed reaction time [15, 16]. Consequently, it is debatable whether these fall techniques would be both effective and trainable for the older adults. Only one study included elderly subjects and suggested that elderly participants were able to learn tuck & roll technique and reduced hip impact force by 8% (8). However, the study utilized self-initiated falls from a kneeling position, which does not reflect falls in daily life. Additionally, none of the studies examined the effect of safe-landing strategy based on the principles of motor learning. The majority of studies solely focused on examining whether training in safe landing strategy changes performance of the falling skill over a limited and short time scale (acquisition). However, to scientifically determine if a new skill has been learned, motor
performance needs to me maintained over longer timescales (retention) and the skill should be able to be performed in other task conditions (transfer).

1.5. Main principles of motor learning

Motor learning is used to describe relatively permanent changes in the capability for motor skills resulted from training or aimed interventions [17]. To scientifically determine if a new motor skill has been learned, the following components of motor leaning need to be examined: short-term motor acquisition, motor transfer and long-term motor retention.

1.6. Short-term motor acquisition

Short-term motor acquisition refers to the improvement in performance of a motor skill immediately following training [17]. A fundamental theory of short-term motor acquisition is that the improved performance over practice is due to the acquisition of more appropriate representations of action that specify the movement dynamics in relation to the task demands [18]. The acquired movement representation is stored in procedural memory so that it can be implicitly and unconsciously retrieved when performing the skill [19].

In the context of safe-falling strategy, performance improvement can be estimated as reduction in the ratio of impact load when using the trained strategy during a fall compared to that when falling prior to training. Previous research suggested that young adults can improve performance of the tuck-and-roll strategy following 30 minutes of training [13].

Although there is abundant data to suggest that motor skills performance at baseline is reduced in older adults, the ability to improve new motor skills performance over practice remains relatively
intact in old age [20]. It should also be noted that while motor learning is possible in older adults, the rate of learning is slower than the healthy young individuals [21]. There is limited evidence that older adults can acquire novel skill of the tuck-and-roll strategy from a kneeling position after training [14]. However, it is unclear whether older adults could acquire the safe-landing technique starting in a standing position. Motor control research suggests that as the task difficulty and complexity increases, the difference in the rate of motor learning between young and old adults also increases [22]. Therefore, it is possible that older adults will exhibit a reduced ability to learn to safely fall when it is performed in standing position. This highlights the importance of examining whether older adults can learn the safe landing strategy in a standing position.

Older adults show a high potential to acquire and further refine complex movements after short-term practice. Specific to falls domain, older adults have been found to improve motor performance in stepping strategies following short-term training [21, 23]. Older adults were able to improve compensatory movement response to recover balance when exposed to repeated external perturbations [23, 24]. Such improvement of the compensatory movement response reflects the ability to acquire novel associations between the external perturbation and motor actions in older adults [23, 24]. Indeed, this slip training has been found to reduce fall incidence by 50% in community dwelling older adults [24]. However, although this collective research suggests that older adults will be able to learn how to fall safely, it is important to note that this stepping training builds upon a well-practiced skill, while safe falling will entail learning a novel motor pattern.

1.7. Motor transfer

Another fundamental aspect of motor learning is developing the capability to transfer
performance of the skill from the practice environment to another environment [17]. Such an ability to generalize the learned skill to other task conditions is defined as motor transfer. From a practical point of view, the transfer principle is significant for establishing effective safe landing skills as falls can happen in diverse and unexpected task conditions.

A classic approach to investigate motor transfer is to examine transfer of the trained limb to the untrained limb. The phenomenon is called as ‘bilateral transfer’ in which improvement in the performance in non-practiced side results from practice with the contralateral side. It has been speculated that the performance of a skill in both sides have the same neural representation of action that specify the elements of movement regardless of the side of the body that skill was performed. Therefore, a person applies the knowledge acquired with practice of one limb about what to do to perform the skill to the initial performance of the skill with the contralateral limb. [25, 26].

Importantly, it has been shown that the rate of learning at transfer task is preserved with aging [26, 27]. In Seidler’s study [27], younger and older participants performed visuomotor aiming task with different conditions of feedback display as a transfer task. The results indicated that despite age-related declines in short-term motor acquisition, both age groups showed an equivalent amount of transfer to the visuomotor aiming tasks. Additionally, a previous study that examined bilateral transfer in ballistic motor training reported that the extent of bilateral transfer was substantial and indistinguishable between the younger and older groups although rate of learning was significantly slower in the older group [26]. The investigations suggested that the underlying processes contributing to motor acquisition and transfer are distinct and that these processes are differentially affected by age [26, 27]. Presumably, the cognitive processes associated with motor acquisition tasks are not required at motor transfer [27]. During the transfer of motor learning, subjects need
to retrieve motor memories and elaborate upon them which require reduced cognitive component compared to motor acquisition [27]. It is possible that the reduced cognitive component for motor transfer allows preserved performance in transfer task with aging.

Although older adults preserve ability to perform motor transfer in fine motor tasks, previous investigations on postural stepping response reported that neither younger nor older group were not able to generalize improvements in stepping responses across directions [24, 28]. Specifically, the improvements made in compensatory backward and forward stepping did not transferred to lateral compensatory stepping for neither younger nor older group [28]. The studies suggested that multidirectional training may be necessary to facilitate generalization of postural stepping responses for any directions of balance loss [28].

1.8. Long-term motor retention

Another fundamental aspect of motor learning is examining the persistence characteristic of improved performance due to practicing a skill. In the context of motor training, long-term retention is considered as the hallmark of a learned motor skill [17]. Especially, since falls occur unexpectedly in a daily life, a safe landing strategy should be stored in long-term memory so that it could be immediately retrieved when a person recognizes loss of balance. Long-term memory can be examined by a long-term retention test that requires a person to produce a required movement response after a period of time during which the learner have not actually practiced the skill. One study on safe landing strategy in forward falling conducted the retention test to examine long-term retention of the trained skill [29]. The study observed that when the safe falling technique was trained with a brief 15-minutes practice in young adults, although there was short-term improvement in performance immediately after the training, this did not result
in long-term retention 3-weeks following training – suggesting that there was no true motor learning [29]. It appears that practice schedules are an important consideration in long-term motor learning [30]. When the skill is practiced more frequently, its representation in long-term memory can be strengthened [17]. Therefore, both increasing duration and frequency of the training might facilitate long-term retention of a safe landing skill.

It has been reported that long-term motor memory was pristinely preserved in older adults while motor learning was significantly slower in the older adults. Smith et al. examined aging effect on long-term retention with a fine motor performance task [19]. The study reported that motor performance was significantly improved when retested 2 years later in both young (10% improvement) and aged (13% improvement) subjects, suggesting that long-term memory in aging can remain well preserved and intact despite age-associated declines in motor speed and central dopaminergic functions [19]. This age-resistant component of long-term motor memory indicates remarkably stable distributed connections in the neuromotor circuitry involved [31]. Therefore, it is promising that older adults can learn and memorize safe landing strategy for an extended time period when providing enough amount of practice.

1.9. Innovative aspects of the current investigation

The purpose of this pilot investigation was to determine if a safe-landing strategy (“tuck-and-roll”) training is an effective approach to reduce fall-related injuries in older adult. The study was designed to address methodological and theoretical limitations of previous investigations on safe landing strategy training. To address methodological limitations of the previous studies, the current study recruited older people, implemented an unexpected falling simulation, and included an active control group. Additionally, the study also applied theoretical principles of motor learning to
determine if a novel safe falling skill has been learned. The present investigation examined not only short-term learning of the tuck-and-roll strategy but also bilateral transfer and 1-week retention effect to investigate the generalizability of the trained landing skill in different falling conditions as well as long-term retention effect which is a hallmark of motor learning. Table 1 summarizes innovative aspects of this investigation.

1.10. Study aims and hypotheses

We therefore explored three primary study aims in healthy older subjects using a standardized side-way falling experiment paradigm. The first aim was to determine whether older adults could reduce the impact severity of falling by having two sessions of training on the safe-landing strategy. We hypothesized that the training group who learned the tuck-and-roll technique would exhibit greater reduction in impact severity than the active control group who were simply exposed to falling trials without receiving instruction. Additionally, it was examined whether the training effect on the right side of falling can be transferred to the left side of falling (i.e., bilateral transfer effect). We hypothesized that there was no difference in impact severity measurements between the right and the left side falling indicating bilateral transfer effect. Lastly, 1-week retention effect of fall strategy training sessions in older adults was investigated. To indicate that there was 1-week retention effect, we hypothesized that the impact severity parameters measured at one-week follow-up assessment would be significantly less than that at the baseline test but not differ from that at the post-assessment.

Additionally, as a secondary aim of the study, we explored whether the training group’s ability to learn the tuck-and-roll strategy could be quantitatively and qualitatively examined. We hypothesized that the quantitative and qualitative analyses would demonstrate improvement of
performance of the tuck-and-roll strategy after training in the training group. Also, it was hypothesized that the improvement of quantitative and qualitative measurements has negative correlation with impact severity parameters.
CHAPTER 2: METHODS

2.1. Participants

Older adults who resided in the local community were recruited through advertisements. Inclusion criteria were designed to include healthy seniors who are capable of safely undergoing the procedures. The inclusion criteria included being age between 55-75 years, weighting between 45-100kg, having height between 150-195cm, having body mass index between 18.5-34.9 kg/m². To minimize the risk of bone injury, we tested healthy bone mass density (t score > -1.0). Adequate muscle strength was defined on being able to complete 5 times sit-to-stand test within 10 seconds. Also, to ensure that the participants have cognitive ability to understand instruction and learn a new skill, we included individuals scoring Montreal Cognitive Assessment (MoCA) over 26. Additionally, to ensure that the tuck-and-roll strategy is a novel motor skill to learn, we recruited individuals without experience of learning the tuck-and-rolling strategy (e.g., Judo, parachuting). Lastly, to have the main training on their dominant side, we included individuals being right handed.

We excluded all individuals with risk factors for conducting a falling experiment. The exclusion criteria included having a history of bone fracture within 5 years, having been diagnosed with osteoporosis or osteopenia, having history of a stroke or a neuromuscular disease (e.g., Multiple Sclerosis, Parkinson's Disease, Huntington’s disease), having a muscular-skeletal problem (e.g., arthritis), having difficulty in rising from a prone position, being pregnant and having susceptibility of bruising or fragile skin (e.g., taking anticoagulant). The exclusion criteria were applied to self-reported data.

All procedures were approved by the University of Illinois at Urbana-Champaign institutional
review board. All participants provided written informed consent prior to taking part in the investigation.

2.2. Sample size

We used relevant studies to compute the sample size needed for detecting a difference of impact loads between the pre (untrained falling strategy) and post (trained the tuck-and-roll strategy) trials. Groen et al. (2010) observed the safe landing training in older adults decreased normalized impact force from 3.4 +/-0.5 (N/kg.g) to 2.4+/-0.4 (N/kg.g) after training the Tuck & Roll strategy in a kneeling position with effect size of 1.69 [14]. Thus, we estimated that a sample size of 7 subjects in the training group would provide 95% power at the 5% level of significance. We also targeted to recruit 7 subjects as an active control group. A post hoc calculation showed an actual power of 95% of normalized impact force in the training group.

2.3. Study design

Figure 3 depicts the experimental procedures. Enrolled participants attended a total of three session over two weeks.

The first visit included initial screening assessment. During the initial screening, bone mineral density measurements were performed with DEXA bone densitometers (Hologic QDR 4500, Hologic Inc, Waltham, MA). Also, the 5 times of sit-to-stand and MoCA tests were conducted subsequently.

After the initial screening assessment, the study participants who satisfied the inclusion/exclusion criteria were randomized to one of two arms 1) the training group (the tuck-and-roll strategy training) or 2) an active control group (repeated falling with their natural
response). The participants were randomly assigned into the two groups using a simple randomization method with 1:1 allocation ratio by computer-generated random numbers.

Following randomization, the participants underwent a series of 6 falls (3 right-side falls and 3 left-side falls) as a baseline assessment (T0baseline). After completion of baseline testing, the training group received introductory training on the tuck-and-roll strategy to learn basics of the strategy (see 2.6). The active control group was not administered the training.

The participants returned to the laboratory in 2 days. During the second visit, an intermediate assessment was conducted prior to the practice where the participants underwent 3 right-side falling trials (T1). Then, the training group received training which focused on learning to apply the tuck-and-roll strategy in the falling experimental setup for 9 falling trials (see 2.6). After each trial, the training group received feedback on their performance. The active control group was also exposed to 9 falling trials but did not receive instruction or feedback on their performance (see 2.7). After the intervention, subjects in both groups were asked to complete 6 falls (3 right-side falls and 3 left-side falls) as a post assessment (T2).

Their third visit occurred 1 week later and only consisted of a series of 6 falls (3 right-side falls and 3 left-side falls) as 1-week retention test (T3retention).

2.4. Falling experimental setup and protocol

Prior to the falling experiment, the participants engaged in 10 minutes of stretching to minimize the risk of injury. Also, the participants were equipped with protective gear including a light-weight helmet, wrist guard, and neck protector.

During the experiments, subjects were made to fall sideways onto a 20cm crash pad by releasing an inextensible tether that supports the participants at a 10° lean from vertical (Figure 4).
This angle is based on previous research to represent values that exceed the capacity of subjects to recover from falling by taking a single step \([32, 33]\). The 10° initial lean angle was obtained by adjusting the length of the tether, so the selected reading was observed from a goniometer. The tether was released via a mechanical catch (a snap shackle). To increase unexpectedness of the release, a time delay between 3-8 seconds was randomly assigned. The order of presentations of the right and left falls was randomized between subjects in all assessments. Prior to tether release, the subjects were instructed to look forward and at eyelevel, and kept the hips and knees extended. Music was played to minimize aural cues of release of the mechanical catch. In the assessment, the subject was instructed to "land on the mat in a way that feels comfortable for you". Additionally, since hip fracture risk was the main interest of the current study, it was emphasized to land on the hip first by restraining from landing on the hand first, taking a step or kneeling.

2.5. Data collection and analyzes

Fall severity was quantified with (a) hip impact force (b) hip impact velocity (c) maximum head acceleration (d) hip impact acceleration. The parameters were selected based on the systemic review study on safe landing strategy \([12]\).

Forceplate (S-Mill, Motekforce Link, Amsterdam, the Netherlands) was utilized to estimate impact force applied on the hip during a fall. The force data were recorded by the CueFors 2 software (Motekforce Link, Amsterdam, the Netherlands) at 500 Hz. Hip impact force was determined as the maximum force in the vertical direction at hip impact, normalized for body weight (Figure 5. (a)). The data were analyzed using custom routines (MATLAB, MathWorks, Natick, MA).

Additionally, a ten-camera motion capture system (VICON, Oxford Metrics, Oxford, England)
was used to collect kinematic data of the lower limb and the head. 16 reflective markers were attached bilaterally on anatomical landmarks on the lower limb and pelvic segments according to VICON plug-in-gait lower body® model (markers located at anterior superior iliac spine, posterior iliac spine, 1/3 surface of the thigh, lateral epicondyle, 1/3 of surface of the shank, lateral malleolus, metatarsal head, and calcaneus). Also, a reflective marker was attached on the anterior head gear. The motion capture system tracked the 3D coordinates of the reflective markers at a sample rate of 100 Hz.

The 3D coordinates of the markers were entered into a VICON Nexus software (VICON, Oxford Metrics, Oxford, England) and calculated hip velocity and head velocity. Then, using a custom MATLAB script, hip impact velocity was calculated as the maximum value of hip vertical velocity prior to impact (Figure 5. (b)). Head acceleration was computed by numerical differentiation of head velocity and subsequently low-pass-filtered with a fourth-order Butterworth filter with a cutoff frequency of 20Hz [14]. Maximum head acceleration was calculated as a maximum value of head vertical acceleration (Figure 5. (c)). We neglected horizontal components of the parameters since it has been shown that they were 10-fold smaller than vertical components and they have relatively little effect on risk for bone fracture during a fall [34].

Lastly, participants wore a wireless inertial sensor, BioStampRC (MC10, Inc., Lexington, MA, USA), on the lower back (L4) to estimate hip impact acceleration. The wireless inertial sensor was utilized since hip impact acceleration was difficult to resolve using motion capture camera system due to marker occlusion at impact during a fall. The device sampled data at 125Hz. The acceleration measured in the inertial sensor was resolved into components associated with a global frame with a custom-made MATLAB [35]. Then the converted 3D acceleration was digitally filtered with forth-order, zero-phase, low-pass Butterworth filter with 15Hz cutoff frequency.
Finally, the hip impact acceleration was identified as maximum hip vertical acceleration with a custom MATLAB script (Figure 5. (d)).

2.6. Intervention of the training group

Participants in the training group received two sessions of training. The first session was an introductory training session that lasted ~30 minutes. During the first session, the participants learned the basics of the tuck-and-roll strategy. The training content was progressive in nature. Fall exercises started in sitting position, followed by falls from a crouching, squatting and standing position (Figure 6).

The second session focused on applying the tuck-and-roll strategy in the falling experimental setup which includes unexpected falling with initial leaning angle (see 2.4.). The session lasted ~60 min and the participants practiced a total of 9 trials of right side falls. Motor learning theory suggests that a varied practice schedule facilitate acquisition of the skill by enhancing initial formation of motor schema [36]. Therefore, the practice was scheduled so that the leaning angle was varied (0°, 10° and 15°; 3 trials per each angle). To enhance learning, the training group received feedback by being informed of their peak impact forces after each trial during the practice. Also, a trained trainer provided descriptive feedback on their performance to help the participants understand what they need to do to improve the skill.

2.7. Control condition

There has been evidence that people can teach themselves how to reduce impact load when exposed to repeated falling trials [29]. Therefore, the control group had falling practice session with the same schedule as the training group without receiving instruction or feedback. In the
second visit, the control group participants also practiced 9 trials of right side falling in 0°, 10° and 15° leaning angle (3 trials per each angle). During the practice trials, the control group was simply instructed to “arrest the fall in any way that feels comfortable to you.” The control group did not receive any instruction or feedback regarding their falling strategies.

2.8. Qualitative assessment of the tuck-and-roll strategy

To determine if the training group learned the tuck-and-roll strategy, both qualitative and quantitative analyses were performed. For the qualitative assessment, a video camera recorded the falls from an anterior point of view. A martial arts expert (Judo club coach at University of Illinois at Urbana-Champaign) scored each video on the following five criteria: (Q1) The body was relaxed during descent and the legs were in a deep squat position before landing on the mat. (Q2) The body was twisted slightly during descent so that the participant could land on the buttock. (Q3) The buttock was landed softly on the mat and the rolling happened smoothly without jerky movement. (Q4) The back was kept flexed during rolling motion so that the participant could maximize the contacting area by touching the mat in order of butt, lower back, back spine shoulder blades, and neck. (Q5) The chin was kept tucked during rolling and the head did not hit the floor when rolling. The videos were rated between 0 to 2, depending on whether the criterion was unperformed (0), partially performed (1), excellently performed (2). The possible total score ranges between 0 and 10.

2.9. Quantitative assessment of the tuck-and-roll strategy

Since the tuck-and-roll technique is characterized by knee flexion and backward rotation during descent, quantitative assessment examined change of the knee flexion angle (sagittal plane)
and hip rotation angle (transverse plane) during descent. Following the convention [37], the knee flexion angle (sagittal plane) was defined as angle between the shank and thigh vectors (Figure 7. (a)). The knee flexion angle was calculated by the VICON Nexus software using kinematic fitting algorithm and filtered with a cut-off frequency of 4Hz [38]. Then, a custom MATLAB code identified change of the knee flexion angle during a fall.

The hip rotation angle (transverse plane) was determined by considering a hip vector that passed through the right anterior superior iliac spine (RASI) and left anterior superior iliac spine (LASI). The angle (α) between the hip vectors at impact and at fall initiation was calculated to estimate hip rotation angle during a fall (Figure 7. (b)). This is an approach similar to that used by Robinovitch [39] to characterize pelvis orientation during falls. The hip rotation angle reflects how near (degree) the site of pelvic impact is to the lateral aspect of the pelvis. A value of α=0° would indicate direct impact to the lateral aspect of the pelvis, whereas α=90° would indicate impact to the posterior aspect of the pelvis [39]. The hip rotation angle at impact was computed with a custom-written program in MATLAB.

2.10. Statistical analysis

Statistical analysis was performed using SPSS for Windows, version 19.0 (IBM, Inc., Chicago, IL). Participant characteristics were compared between the groups with independent t-tests. Baseline assessment was compared between the groups with multivariate analysis of variance (MANOVA) for impact severity parameters with group (training, control) by falling side (right, left) factors. To test the first hypothesis (short-term training effect), repeated-measures analysis of variance (repeated-measures ANOVA) was performed with time (T0baseline, T1, T2) as within-subject factor and group (training, control) as between subject factors for each impact severity
parameter, respectively. When a significant group \times time interaction was present, ANCOVA tests were performed with group as a fixed factor and T0_{baseline} as covariance to explore whether there was group effect when baseline was controlled at each time (T1 and T2). To test the second hypothesis (bilateral transfer effect), repeated-measures analysis of covariance (repeated-measures ANCOVA) was conducted for impact severity parameters with falling-side (right, left) as within-subject factor, group (training, control) as between-subject factors and T0_{baseline} as covariate. To control for baseline differences between the groups, impact severity values at T0_{baseline} was entered as a covariant. To test the third hypothesis (1-week retention effect), T3_{retention} was compared with T0_{baseline} and T2, respectively. Firstly, repeated-measures ANOVA was conducted to compare T0_{baseline} and T3_{retention}, with time (T0_{baseline}, T3_{retention}) as within-subject factor, group (training, control) as between subject factors. Also, repeated-measures ANCOVA was conducted for impact severity parameters with time (T2, T3_{retention}) as within-subject factor, group (training, control) as between subject factors and T0_{baseline}.

For quantitative evaluation of falling performance, knee flexion angle and hip rotation angle were compared across visits and between groups using repeated-measures ANOVA with time (T0_{baseline}, T1, T2) as within-subject factor and group (training, control) as between subject factors. Also, it was examined whether impact severity measurements were associated with quantitative/qualitative evaluation of the tuck-and-roll performance. Due to the small sample size, Spearman ranked order correlation was conducted to test correlation between impact severity parameters and quantitative (knee flexion angle, hip rotation angle) and qualitative (scores) evaluation. Measure of eta-squared (\eta^2) was obtained as the effect size for ANOVA analysis. Conventionally, \eta^2 values of 0.02, 0.13 and 0.26 are considered to represent small, medium and
large effects, respectively. According to the hypotheses, all analyses used one-sided tests, and $p$ values equal or less than 0.05 were considered statistically significant.
CHAPTER 3: RESULTS

3.1. Participant flow

Participant flow through recruitment and enrollment is outlined in Figure 8. A total of 37 of individuals who met inclusion criteria were assessed for eligibility. After screening, a total of 17 participants were deemed eligible. Participants were excluded for various reasons including low bone density measurements, low cognitive test scores, self-reported muscular-skeletal disease, and being left-handed.

The remaining 17 participants were randomly assigned into the two groups (i.e., the training and the active control group). After the initial session, one participant from each group discontinued the study due to mild back and hip soreness. One participant from the training group discontinued the study after the second session due to mild neck soreness. Finally, a total of 14 participants completed the study (n=7 training; n=7 control).

3.2. Participant characteristics

A comparison of training and control group characteristics are reported in Table 2. The average age of the participants was 63.9±5.6 years (range: 55-73 years). Ten of the 14 participants (72%) were male. The gender distribution was matched between the groups. Although the training group performed significantly better in 5 times sit to stand (t(12)=−3.89, p<0.01) and MoCA (t(12)=−3.86 p=0.01), all participants in the both groups performed above cutoff scores of 5 times sit to stand and MoCA tests. Also, 5times sit-to-stand and MoCA score did not have significant correlation with any of the impact severity parameters (p’s>0.05). No other characteristics showed significant difference between the groups (p’s>0.05). Overall, this performance indicates that the sample consisted of healthy young-older adults.
3.3. Baseline assessment

To assess whether there were pre-training differences in impact severity between groups and falling-side, we compared impact severity parameters at baseline with group (training, control) × falling side (right, left) factors. The MANOVA revealed that the training group had significantly greater hip impact force \( F(1, 14)=16.4, p<0.01, \eta^2=0.86 \), hip impact velocity \( F(1, 14)=7.00, p=0.02, \eta^2=0.88 \) and hip impact acceleration \( F(1, 14)=7.36, p=0.02, \eta^2=0.88 \) than the control group at baseline assessment. The head acceleration showed tendency to be greater in the training group than the control group but the difference did not reach significant level \( F(1, 14)=3.73, p=0.07, \eta^2=0.79 \). There was no significant effect of side nor an interaction effect in all impact severity measurements \( (p’s>0.05) \).

3.4. Short-term training effect on impact severity measurements

Figure 9 demonstrates impact severity measurements as a function of group and time. To examine the short-term training effect, repeated measure ANOVA was conducted with time \( (T0_{\text{baseline}}, T1, T2) \) as within-subject factor and group (training, control) as between subject factors. The results revealed that there was significant difference as a function of time in all impact severity measurements (normalized hip impact force: \( F(2,24)=11.8, p=0.00, \eta^2=0.95 \); hip impact velocity: \( F(2,24)=5.12, p=0.01, \eta^2=0.84 \); hip impact acceleration: \( F(2,24)=21.2, p<0.01, \eta^2=0.96 \); head acceleration: \( F(2,24)=7.29, p<0.01, \eta^2=0.88 \)). Also, there was significant group × time effect in hip impact force \( (F(2, 24)=4.82, p=0.02, \eta^2=0.81 \), hip impact acceleration \( (F(2,24)=5.73, p<0.01, \eta^2=0.85) \), and head acceleration \( (F(2,24)=3.83, p=0.02, \eta^2=0.81 \). There was no significant group × time effect on hip impact velocity \( (F(2,24)=0.97, p=0.20, \eta^2=0.49) \). The results indicate that while
both groups reduced impact severity measures over time, the training group had significantly greater reduction in hip impact force, hip impact acceleration, and head acceleration compared to the control group.

Specifically, at T1, the training group reduced hip impact force by 23% while the control group reduced it by 11% compared to T0_{baseline}. Additionally, further reduction in hip impact force was observed at T2 in both groups. The training group reduced hip impact force by 33% while the control group reduced 16% at T2 compared to T0_{baseline}.

Hip impact acceleration showed 30% reduction in the training group and 18% reduction in the control group at T1 compared to T0_{baseline}. At T2, further reduction in hip impact acceleration was observed in the training group (38% of reduction compared to T0_{baseline}) but not in the control group.

Also, there was significant reduction in head acceleration in both groups. At T1, the training group reduced head impact acceleration by 45% while the control group reduced it by 21% compared to T0_{baseline}. At T2, further reduction in head impact acceleration was observed in the training group (59% reduction compared to T0_{baseline}) but not in the control group.

Additionally, for the impact severity parameters with group × time effect, we further explored whether there was group effect at each time point (T1, T2) when baseline was controlled. ANCOVA was performed with group as a fixed factor and T0_{baseline} as a covariate for each time (T1, T2). The results showed that normalized hip impact force and hip impact acceleration had a significant group effect at T2 (normalized hip impact force: F_{(1, 11)}=3.01, p=0.05, η^2=0.75; hip impact acceleration: F_{(1, 11)}=3.16, p=0.05, η^2=0.90) but not at T1 (normalized hip impact force: F_{(1, 11)}=0.96, p=0.17; hip impact acceleration: F_{(1, 11)}=1.51, p=0.12). Head acceleration was not significantly different between the groups at either time point (T1: F_{(1, 11)}=0.39, p=0.42; T2: F_{(1, 11)}=0.94, p=0.17).
3.5. Bilateral transfer effect

To assess whether there was transfer of the falling strategy, repeated-measures ANCOVA was conducted with falling-side (Right, Left) as within-subject factor, group (training, control) as between-subject factors and T0baseline as covariate. Figure 10 illustrates impact severity measures as a function of side and group in T2 and T3retention.

In T2, there was no difference in impact severity between sides in normalized hip impact force ($F_{(1,11)}=0.25, p=0.63$), hip impact velocity ($F_{(1,11)}=0.23, p=0.65$), hip impact acceleration ($F_{(1,11)}=0.80, p=0.39$) and head acceleration ($F_{(1,11)}=0.15, p=0.70$). Also, there was no side × group interaction effect in any of the impact severity parameters (normalized hip impact force: $F_{(1,11)}=0.00, p=0.99$; hip impact velocity: $F_{(1,11)}=0.30, p=0.59$; hip impact acceleration: $F_{(1,11)}=0.14, p=0.72$; head acceleration: $F_{(1,11)}=1.23, p=0.29$).

Similarly, at T3retention, there was no difference in impact severity between sides in normalized hip impact force ($F_{(1,11)}=0.00, p=0.98$), hip impact velocity ($F_{(1,11)}=0.11, p=0.75$), hip impact acceleration ($F_{(1,11)}=0.01, p=0.94$) and head acceleration ($F_{(1,11)}=0.38, p=0.55$). Also, there was no falling-side × group interaction effect in all impact severity parameters (normalized hip impact force: $F_{(1,11)}=0.25, p=0.62$; hip impact velocity: $F_{(1,11)}=2.18, p=0.17$; hip impact acceleration: $F_{(1,11)}=0.01, p=0.98$; head acceleration: $F_{(1,11)}=0.11, p=0.75$).

These observations indicate there was bilateral transfer of the training in both T2 and T3retention.

3.6. 1-week retention effect

To examine whether the safe-falling strategy was retained over a week, the impact severity measurements at 1-week retention test was compared to that at the baseline test with repeated-measures ANOVA with time (T0baseline, T3retention) × group (training, control) factors. All of the
impact severity parameters at $T_{3\text{ retention}}$ was significantly less than that at $T_{0\text{ baseline}}$ (normalized hip impact force: $F_{(1,12)}=22.3, \ p<0.01, \ \eta^2=0.67$; hip impact velocity: $F_{(1,12)}=11.6, \ p<0.01, \ \eta^2=0.49$; hip impact acceleration: $F_{(1,12)}=37.6, \ p<0.01, \ \eta^2=0.76$; head acceleration: $F_{(1,12)}=13.3, \ p<0.01, \ \eta^2=0.53$). Also, there was time × group interaction effect in hip impact force ($F_{(1,12)}=3.24, \ p=0.05, \ \eta^2=0.21$), hip impact acceleration ($F_{(1,12)}=6.80, \ p=0.01, \ \eta^2=0.36$) and head acceleration ($F_{(1,12)}=5.45, \ p=0.02, \ \eta^2=0.31$) indicating that the reduction at $T_{3\text{ retention}}$ compared to $T_{0\text{ baseline}}$ was greater in the training group than the control group.

Additionally, it was examined whether impact severity measures at $T_{3\text{ retention}}$ had similar values with that at T2, repeated-measures ANCOVA was conducted with time ($T_2$, $T_{3\text{ retention}}$) as a within-subject factor, group (training, control) as between-subject factors, and $T_{0\text{ baseline}}$ as covariate to control for baseline differences between the groups. There was no significant difference between $T_2$ and $T_{3\text{ retention}}$ in hip impact velocity ($F_{(1,11)}=0.23, \ p=0.15$), hip impact acceleration ($F_{(1,11)}=1.04, \ p=0.33$) or head acceleration ($F_{(1,11)}=1.96, \ p=0.09$) when controlling for baseline. However, there was a significant difference between $T_2$ and $T_{3\text{ retention}}$ in normalized hip impact force ($F_{(1,11)}=5.17, \ p=0.02, \ \eta^2=0.32$). Also, normalized hip impact force had time × group interaction effect ($F_{(1,11)}=7.96, \ p=0.01, \ \eta^2=0.25$) while hip impact velocity ($F_{(1,11)}=0.17, \ p=0.69$), hip impact acceleration: $F_{(1,11)}=1.40, \ p=0.26$) and head acceleration($F_{(1,11)}=0.02, \ p=0.44$) did not.

Overall, the results indicate that the training group showed complete 1-week retention effect in hip impact velocity, hip impact acceleration and head acceleration while only partial retention in normalized hip impact force. On the other hand, the control group exhibited complete 1-week retention effect in all impact severity parameters.

3.7. Qualitative evaluation on the tuck-and-roll performance
To determine if the training group learned the tuck-and-roll strategy, both qualitative and quantitative analysis was performed. Table 3 demonstrates qualitative evaluation of the tuck-and-roll performance. On a ten-point qualitative scale, the participants showed moderate performance on the tuck-and-roll strategy at T1 and good performance at T2 and T3 assessment. Among the items in the performance competency checklists, ‘The chin was kept tucked during rolling and the head did not hit the floor when rolling’ showed the lowest average score. However, the item showed the greatest improvement across the sessions having 87% increase in the score from T1 to T2 and 42% increase from T2 to T3. The correlation analysis between qualitative evaluation and impact severity parameters revealed that scores of chin tucking criterion (Q5) had moderate negative correlation with head acceleration ($\rho=-0.40, p=0.02$). No other criteria were significantly correlated with impact severity parameters ($p’s>0.05$).

3.8. Quantitative evaluation (joint kinematics) on the tuck-and-roll performance

To confirm that the participants in the training group performed the tuck-and-roll strategy according to the instruction, quantitative analysis on joint movement was also evaluated.

Figure 11 demonstrates the amount of change of the knee flexion angle and the hip rotation angle during a fall as a function of group (training, control) × time (T0baseline, T1, T2, T3retention). The knee flexion angle was significantly increased between the time ($F_{(2,24)}= 14.3, p<0.01, \eta^2=0.93$). Also, there was significant group × time effect in the knee flexion angle ($F_{(2,24)}= 12.6, p<0.01, \eta^2=0.93$). This result indicated that although knee flexion angle increased over time in both groups, the training group had significantly greater change.

Specifically, the training group significantly increased the knee flexion angle by 27% at T1, by 46% at T2 and by 40% at T3retention compared T0baseline ($p’s<0.05$). On the other hand, the control
group did not show statistically significant change of the knee flexion angle across time ($p$'s $>$ 0.05).

These results suggest that participants in the training group executed the tucking motion by increasing knee flexion angle over the tests while the control group did not.

The hip rotation angle at impact was not significantly different as a function of time ($F_{(2,24)}$ = 1.75, $p$ = 0.20). However, there was group $\times$ time effect in the hip rotation angle at impact ($F_{(2,24)}$ = 3.32, $p$ = 0.03, $\eta^2$ = 0.77).

The result suggests that the training group increased the hip rotation angle at impact (increased by 58% at T1, by 36% at T2 and by 69% at T3$_{retention}$) indicating that the participants rotated further backward when landing compared to T0$_{baseline}$. On the contrary, the control group decreased the hip rotation angle (by -9% at T1, by -35% at T2 and by -13% at T3$_{retention}$) indicating that the participants fell further toward on their sides compared to T0$_{baseline}$.

3.9. Correlation between joint kinematics and impact severity measurements

To examine if quantitative evaluation on the tuck-and-roll performance, represented by joint kinematics, is related to impact severity, correlation analysis between joint kinematics and impact severity measurements was conducted.

The knee flexion angle at impact was moderately to strongly correlated with the impact severity measurements (hip impact force: $\rho$ = -0.75, $p$ = 0.00; hip impact velocity: $\rho$ = -0.59, $p$ < 0.01; hip impact acceleration: $\rho$ = -0.60, $p$ < 0.01; head impact acceleration: $\rho$ = -0.44, $p$ = 0.01) (Figure 12).

On the contrary, the hip angle at impact was not significantly correlated with any of the impact severity measurements ($p$'s $>$ 0.05).
CHAPTER 4: DISCUSSION

4.1. General summary

The purpose of this investigation was to determine if a safe landing strategy (“tuck-and-roll”) training is an effective approach to reduce fall related injuries in older adults. A total of 17 healthy older individuals (9 training group and 8 control group) participated in the study. The main result of the present study was that after two sessions of the training, the training group learned the tuck-and-roll strategy which resulted in 33% reduction in hip impact force, 59% reduction in maximum head acceleration and 38% reduction in hip impact acceleration. By comparing these results with those of the active control group, we conclude that this gain might be due to effectiveness of the falling strategy. Importantly, the subjects were able to utilize the strategy that was acquired through the right-side falling practice to the left-side falling (i.e., bilateral transfer effect). Furthermore, the participants partially retained the effectiveness of the tuck-and-roll strategy for 1-week. However, the current study also observed potential risks of the tuck-and-roll strategy, such as head impact, when the strategy was not performed properly. Given the promising results of the current study, developing comprehensive training program to teach the safe landing strategy for older adults is important to target fall related injury prevention.

4.2. Effectiveness of the tuck-and-roll strategy in reducing impact severity

Consistent with the hypothesis, training on the tuck-and-roll strategy resulted in a decrease in hip impact force (reduction of 1.21 N/kg/g or 33%) and head acceleration (reduction of 4.67g or 59%) in the training group. Although the control group also showed significant decrease of the hip impact force (reduction of 0.45N/kg/g or 16%) after exposure to repeated falling trials, the amount
of reduction was greater in the training group than that in the control group. This result implies that the short-term gain of the training group might be due to the effectiveness of the falling strategy itself.

The mechanism by which the tuck-and-roll techniques are effective in reducing impact severity is the smaller amount of energy dissipation at impact as a result of optimal distribution of the impact force applied to the body part along the contact path while rolling [40]. It was notable that the hip impact velocity, which is one of the main predictors of hip impact force, was not influences the tuck-and-roll strategy. This suggests that other features of the movement such as rolling on after hip impact may indeed play an important role in the reduction of hip impact force [41]. To be specific, rolling results in a higher kinetic energy of the body after impact, which might result in a smaller amount of kinetic energy transformed into strain energy [42]. This higher kinetic energy related to the rolling motion might result in lack of reduction in hip impact velocity.

4.3. Comparison with previous studies

To our knowledge, this is the first study to investigate ability of older adults to utilize the tuck-and-roll strategy from a standing height fall (average age: 64.3±4.4 years). The majority of the previous studies that examined effectiveness of the tuck-and-roll strategy were conducted with young adults (average age: 28.0±13.2 years) [13, 40, 43]. Despite the age difference, the ability of the training group to reduce their impact force by utilizing the tuck-and-roll strategy (effect size: 2.01, 95% CI: 1.56-2.47) corroborates the result of the previous studies with young adults (effect size: 2.70, 95% CI: 1.09-4.31) [12]. This observation is consistent with the notion that although motor skills performance at baseline might be reduced in older adults, they can still learn novel skills with practice [20]. However, it should be also noted that the previous studies with young
subjects acquired the gain after only 30 minutes of training [40], whereas the current study provided total ~90 minutes of training over two sessions. Indeed, although motor learning is possible in older adults, the rate of learning is slower than the young adults[21]. This highlights the importance of providing sufficient training when incorporating the current approach in a program targeting fall related injury prevention.

4.4. Clinical significance of the effectiveness of the tuck-and-roll strategy

The potential relevance of the tuck-and-roll training for hip fracture prevention could be estimated by comparing the observed hip impact force reduction of 33% to the effect of external devices that are designed to attenuate hip impact force. Specifically, it has been reported that hip impact force could be attenuated by 9-19% by use of hip protectors [44] and upto 34% by compliant flooring [45]. Hence, this suggests that the tuck-and-roll strategy might have similar or even better effects for hip fracture prevention compared to these external devices. The limitations of hip protectors (e.g., poor compliance) and compliant floors (e.g., cost) further highlight the importance of the current findings.

4.5. Quantitative and qualitative analysis

The current study qualitatively and quantitatively confirmed that the training group was successful in learning basic of the tuck-and-roll strategy within two sessions of training. Qualitative analysis determined that the training group significantly improved their performance from T1 (4.6 points out of 10 scale) to T2 (7.4 points out of 10 scale). Given that T1 was conducted after brief introduction of the strategy and T2 was assessed after having 9 practice trials and receiving personalized feedback on their performance, such an improvement seems to be realistic.
to expect. Despite the improvement, only 3 out of 7 participants reached near-optimal level of performance (9 points out of 10 scale) at T2. This suggest that a further improvement of the performance could be anticipated with additional training sessions which might result in greater reduction of impact severity.

The quantitative analysis also supported that the older adults were capable of following specific instructions of the tuck-and-roll strategy. The training group performed ‘tucking motion’ by increasing knee flexion angle (knee angle = 124±5 degree) indicating that the participants were positioned in a deep squat position prior to landing. Also, the training group rotated their trunk in longitudinal axis (rotation angle = 49±4 degree) so that the participants could land on the posterior hip to facilitate rolling along the back.

Additionally, the observation that knee flexion angle has moderate correlation with impact severity measurements (rho=0.56~0.65) suggested that the knee flexion had significant contribution to the resulting impact severity. Theoretically, flexion of the knee could provide several benefits. First, the increased knee flexion reduces the horizontal excursion of the center of the gravity with respect to the ankles and thereby reducing moment of arm while falling. This reduction in the moment arm reduces gravitational torque during a fall resulting in decreased impact energy applied to the body. Additionally, the flexion of the knee induces tucked position making the body “curl into a ball” promoting smoother rolling after the impact. [34]. Therefore, it is promising to investigate whether flexing knees itself could contribute to reducing impact severity. It is logical to assume that this training would be easier since performance on simple motor skills is less influenced by aging then a complex motor skill [20].

4.6. Transfer
Consistent with our hypothesis, the training effect of the falling strategy transferred from the trained falling side (i.e., right-side) to the non-trained falling side (i.e., left-side). It has been known that bilateral transfer requires mirror imaged (i.e., bilaterally symmetrical) motor responses [46]. Specifically, for bilateral transfer of the tuck-and-roll strategy, a person should rotate the trunk clockwise for the right-side falling and counter-clockwise for the left-side falling to land on the posterior hip. However, despite the difference in response, it has been speculated that performance of a motor skill in bilateral sides have the same neuromuscular representation of action that specify the elements of movement [25, 26]. Therefore, it is likely that the participants were able to apply the same motor program that was formed during training the tuck-and-roll strategy in the right-side falling to the left-side falling.

Typically, the mechanism of sharing the motor program in bilateral transfer is explained in the context of three different models. i) the callosal access model, ii) the proficiency model and iii) the cross activation model [46]. According to the callosal access model, motor programs are saved in the dominant (mainly left) hemisphere, regardless of the training side [47]. As a consequence, the dominant-side performance will have direct access to these motor programs while the subdominant-side performance will have indirect access via the corpus callosum. The proficiency model [48] assumes the generation of unilateral engrams that are stored in motor areas contralateral to the trained-side. The developed engrams will transfer to the motor centers located in the opposite hemisphere when executing bilateral motor performance. The cross activation model [49] suggests the formation of two motor programs, one located in each hemisphere, which are thought to operate in a coupled manner. In this model, the untrained-side motor cortex will receive a copy of the updated motor program which will work independently from trained-side motor cortex when a subject is required to perform a skill in the untrained-side.
Also, the current results support the previous notion that the rate of learning at transfer task is preserved with aging [26, 27]. During the transfer of motor learning, subjects need to retrieve motor memories and elaborate upon them which require reduced cognitive component compared to motor acquisition [27]. It is possible that the reduced cognitive component for motor transfer allows preserved performance in transfer task with aging. Additionally, it should be noted that the participants had training on the right-side which is their dominant hand side. Several studies have suggested that the subdominant-side performance benefits more from dominant-side training than does the dominant-side from subdominant-side training [26, 46]. Therefore, it might be important to train in the dominant side to optimize bilateral transfer effect.

The observation regarding transfer effect is important in generalizing the effectiveness of training since a fall can happen in a multitude of ways. It is also promising to investigate if the training effect could be transferred into backward falls since the basic of the tuck-and-roll strategy is changing a side-way fall into a backward fall. Additionally, ability to modulate impact severity utilizing the protective strategy might be influenced by the activity of a faller when losing balance, such as walking, reaching, turning or rising [12]. Therefore, further investigations with various intrinsic, environmental and situational manipulations is warranted to examine the generalizability of the effectiveness of the fall technique.

4.7. Retention

Contrary to our expectation, the participants in the training group exhibited complete 1-week retention in reducing head acceleration and hip impact acceleration, whereas the hip impact force was considerably greater in the follow-up session compared with the test at the end of the short-term learning session (T2). However, it is worth noting that the hip impact force at 1-week follow-
up was still significantly less than the baseline as well as early acquisition phase (T1). Therefore, the gain in follow-up session may be considered as partial retention. It seems that the central nervous system was attempting to recall and execute the motor elements of the tuck-and-roll strategy, but only partially succeeded due to deterioration in motor memory over 1-week period.

It has been suggested that long-term memory in aging can remain well preserved and intact despite age-associated declines in motor speed and central dopaminergic functions [19]. Therefore, we postulate that the observed deficiency of retention is not age-associated but resulted from insufficient amount of practice or inappropriate practice schedule which are an important consideration in long-term motor learning [30].

In the current study, the participants had a brief introduction session in the first session and an intensive practice session with 9 falling trials in the second session. Potentially, although the two sessions of training resulted in short-term acquisition of the skill, it may be insufficient to enhance complete long-term retention effect. It has been suggested that “overlearning” with extra practice after initial skill acquisition could enhance long-term motor memory by promoting stable distributed connections in the neuromotor circuitry involved [31, 50]. Therefore, it is possible that if additional practice sessions were provided, participants might have exhibited greater retention.

Another important aspect of training associated with long-term memory is temporal spacing between repetitions of skill [51]. Previous research has demonstrated that distributing practice across days, compared to within days, leads to increase performance and learning of complex motor skills [51]. The longer inter-session intervals of practice provides extended periods of inactivity, rest or even sleep after practice which are important for the consolidation of long-term memories [51]. It should be note that although the current study provided two sessions of the training, the practice trials were concentrated in the second session. Therefore, it is promising to
modify the training schedule by distributing practice over days to enhance long-term retention of the tuck-and-roll strategy [17].

4.8. Implication of the control group

It should also be noted that the baseline values of the impact severity parameters were significantly greater in the training group than the control group. Consequently, despite greater reduction of the impact severity in the training group, the values of impact severity themselves were not different between the groups at T2. Potentially, the control group might utilize an effective protective response from the baseline. If so, the smaller reduction of impact severity in the control group may be related to a floor effect, as further reduction was unnecessary or impossible.

Another important observation is that the control group also had significant reduction in hip impact force over time. Although the amount of reduction was less than that of the training group, the 16% of the reduction of hip impact force in the control group was significant. This observation is noteworthy because it is the first time that healthy older subjects have been exhibited capability of self-learning in reducing impact severity over a series of falls. This is consistent with antidotal accounts that individuals who frequently fall know how to fall safely [52]. Similar results were shown in a previous study with young adults which found that the young subjects were able to find ways to reduce wrist impact force by simply being exposed to repeated falling trials in a forward fall [29].

We attribute this to the phenomenon of “implicit learning” which means the features of motor skills can be learned and used, even though the learner is not consciously aware of the specific characteristics of those features [53]. Specifically, the repeated falls may lead to individuals teaching themselves how to improve their fall-arrest techniques, thereby reducing their risk for
fall-related injury, without consciously realizing it. Importantly, the current study and the previous study with young adults both found that the self-learning group acquired complete long-term retention effect while the group that received instruction of a specific falling skill did not. This reflects the benefit of implicit learning in long-term motor memory since the process does not detract cognitive resource to remember and apply the explicit instruction [53].

4.9. Significance

Despite decades of research demonstrating that fall incidence can be reduced with targeted-intervention, fall-related death rate has increased over the last fifteen years [54]. We believe that this novel movement-centric approach to enhance safe landing responses represents a potential addition to currently developed tools (e.g., fall prevention programs, osteoporosis medication, hip protectors, and compliant flooring) to reduce fall related injury. The potential benefit of safe fall training is highlight when one considers that falls are still common in individuals who participate in successful fall prevention programs, [7, 8]. Although the development of such programs for general older population is a challenging, the current investigation served as a starting point for achieving feasibility of this task.

4.10. Potential risk of the strategy

Although the current study found benefit of the tuck-and-roll strategy in reducing impact severity, a potential risk of the strategy was observed as well. There were two participants who dropped out during training due to mild soreness on the neck and back. Although majority of the participants underwent the training procedure safely, this observation implies a potential risk of the strategy which might lead to adverse consequence when performed inappropriately.
Especially, the tuck-and-roll strategy might increase the risk of head impact since the head naturally gets near to the ground when rolling on the back. To maximize clearance between the head and the ground for head protection, the participants were instructed to tuck the chin in while rolling. However, participants in the training group had difficulty tucking their chin during falling. The qualitative evaluation in executing the instruction scoring the lowest score on the chin tuck criterion (Q5). Specifically, the score was 0.1 out of 2 scale at T1 and 0.8 at T2 indicating that the motion has not been thoroughly learned until the end of the acquisition session. The reason for the lack of chin tuck is unclear. Potentially, age-related muscle loss (i.e., sarcopenia) [55] might result in diminishing ability of controlling the head for older adults.

Also, it should be noted that although the hip impact force and head acceleration considerably reduced with the tuck-and-roll strategy, repeated application of stress lower than the fracture load could also cause injury [56]. Therefore, while repetition is essential in learning a skill, it might increase risk of injury especially in the early phase of learning since the skill might be improperly performed. Further investigation is necessary to determine safe training procedure for older adults to minimize the risk of injury of the strategy.

4.11. Limitations

Despite the novel observations of this current investigation, there is a number of limitations in this study. A major limitation of the study is the small sample size. While both hip impact and head impact were primary outcomes of interest, the lack of data related to head impact in previous studies precluded an appropriate power estimate. Consequently, there was lack of power (power=34%) to detect a group effect of head acceleration at post-test. A post-hoc calculation
based on head acceleration data showed that total 36 participants (18 participants in each group) are needed to provide 95% power at the 5% level of significance. As a pilot study, the current investigation would further serve as a reference to calculate sample size for the future study.

The second limitation is that the baseline values were not equivalent between groups. Due to lack of previous investigation on side-way falls in older adults, there was no criterion to be considered when planning to match the baseline values between the groups. However, the current study controlled the baseline values as a covariate in the statistical analysis to minimize baseline differences.

Another limitation of the study is unique characteristics of the subjects which might compromise generalizability of the results. First, the subject groups were not gender balanced. A majority of female individuals were excluded due to lower bone mass density. With only two of the 14 subjects being female, we cannot be certain that the results are representative for the general population of older females. Also, for safety reasons, the current study only included healthy older adults who are above average in terms of their physical fitness. It has been speculated that average elderly individuals might have diminished ability to perform the safe landing strategy because of reduced muscle strength, belated detection of imbalance and delayed reaction time [15, 16]. Further investigation is necessary by expanding the population to be included.

A further limitation is that as in any laboratory study including postural perturbations, questions exist regarding how accurately the experiments simulate real-life falls. First, we utilized “tether release” method to simulate balance loss to initiate a side-way-fall. Although this method has been utilized in a number of experimental paradigms [29, 34, 39], this method has no initial velocity unlike an actual trip or slip during walking [57]. However, while this technique does not replicate the initial momentum during a real-world fall, it allows researchers a repeatable and
controlled experimental protocol to induce a loss of balance [57]. Additionally, it is notable that the average impact velocity measured in the current study (2.41±0.44 m/s) is similar to real world falls (2.14±0.63 m/s)[58]. Second, while our subjects did not know the exact time of release, they knew that a fall was about to happen, and this allowed them to pre-plan their falling strategy. The pre-planning would not be available in a truly unexpected fall. Third, it is possible that subjects may have been less fearful of falling on to a soft mattress than onto a rigid surface. Further research is needed to examine the applicability of the tuck-and-roll technique in a more real-life like experimental setting.
CHAPTER 5: CONCLUSION

Healthy older adults can learn the tuck-and-roll strategy to reduce impact severity during a side-way fall after two sessions of training. This reduction was greater than that of the control group suggesting that this gain might be due to effectiveness of the falling strategy. Also, the subjects were able to utilize the strategy that was acquired through the right-side falling practice to the left-side falling (i.e., bilateral transfer effect). However, only partial retention of the skill was found at 1-week follow up test. Development of more comprehensive training programs and diverse testing conditions are warranted to optimize safety and generalizability of the benefits of the fall strategy. Future research should focus on effectiveness of the skill to more diverse population who are at risk of falling.
**TABLES**

**Table 1.** A brief summary of the shortcomings in the extant literature addressed in the present proposal

<table>
<thead>
<tr>
<th>Previous studies</th>
<th>The current project</th>
</tr>
</thead>
<tbody>
<tr>
<td>• were conducted with young adults</td>
<td>• focused on older adults</td>
</tr>
<tr>
<td>• mainly utilized expected falls or falls in kneeling position</td>
<td>• examined unexpected falls in a standing position</td>
</tr>
<tr>
<td>• lacked control group</td>
<td>• included an active control group</td>
</tr>
<tr>
<td>• focused only on short term changes in performance</td>
<td>• examined motor transfer and retention</td>
</tr>
</tbody>
</table>
Table 2. Participant demographics

<table>
<thead>
<tr>
<th></th>
<th>Training</th>
<th>Control</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>N</strong></td>
<td>7 (2F/ 5M)</td>
<td>7 (2F/ 5M)</td>
<td>--</td>
</tr>
<tr>
<td><strong>Age (yrs)</strong></td>
<td>64.3 +/-4.4</td>
<td>63.5 +/-6.6</td>
<td>0.79</td>
</tr>
<tr>
<td><strong>Height (cm)</strong></td>
<td>171.9 +/-5.7</td>
<td>169.6 +/-8.0</td>
<td>0.55</td>
</tr>
<tr>
<td><strong>Weight (kg)</strong></td>
<td>71.3 +/-10.5</td>
<td>69.7 +/-11.9</td>
<td>0.80</td>
</tr>
<tr>
<td><strong>BMI(kg/m²)</strong></td>
<td>24.0 +/-3.4</td>
<td>24.4 +/-5.2</td>
<td>0.87</td>
</tr>
<tr>
<td><strong>Bone Mass Density (t-score)</strong></td>
<td>-0.42 +/-0.84</td>
<td>0.00 +/-0.92</td>
<td>0.43</td>
</tr>
<tr>
<td><strong>5 times sit to stand (sec)</strong></td>
<td>6.07 +/-1.01</td>
<td>7.99 +/-0.83</td>
<td>*&lt;0.01</td>
</tr>
<tr>
<td><strong>MoCA</strong></td>
<td>29.7 +/-0.5</td>
<td>27.9 +/-1.5</td>
<td>*0.01</td>
</tr>
</tbody>
</table>
Table 3. Qualitative evaluation of the tuck-and-roll performance

<table>
<thead>
<tr>
<th>Criterion</th>
<th>T1</th>
<th>T2</th>
<th>T3 retention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1. The body was relaxed during descent and the legs were in a deep squat position before landing on the mat.</td>
<td>1.3</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Q2. The body was twisted slightly during descent so that the participant could land on the buttock.</td>
<td>1.1</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Q3. The buttock was landed softly on the mat and the rolling happened smoothly without jerky movement.</td>
<td>0.9</td>
<td>1.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Q4. The back was kept flexed during rolling motion so that the participant could maximize the contacting area by touching the mat in order of butt, lower back, back spine shoulder blades, and neck.</td>
<td>1.1</td>
<td>1.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Q5. The chin was kept tucked during rolling and the head did not hit the floor when rolling.</td>
<td>0.1</td>
<td>0.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Total</td>
<td>4.6</td>
<td>7.4</td>
<td>8.4</td>
</tr>
</tbody>
</table>

NOTE. Scores for each criterion range from 0 to 2, depending on whether the criterion was not performed (0), partially performed (1), or excellently performed (2). The total score ranges between 0-10.
**Figure 1.** Effect size (Hedge’s g) of safe landing
Figure 2. Schematic representation of tuck & rolling
**Figure 3.** Experimental procedures

- **1st visit**
  - Initial screening
  - Randomization
  - Baseline test (T0_{baseline})
  - Introductory training on tuck and roll strategy

- **2nd visit**
  - Training group
    - 2 DAYS
    - Intermediate test (T1)
    - Training on tuck and roll strategy

- **3rd visit**
  - Control group
    - Falling trials with a natural response
  - 1-week retention test (T3_{retention})
  - Post test (T2)
Figure 4. Experimental setup of a falling simulation
Figure 5. Impact severity parameters–time profile during a sideway fall of baseline and post-assessment. (a) Normalized force (b) Hip velocity (c) Hip acceleration (d) Head acceleration
Figure 6. Tuck-and-roll training progression
Figure 7. Definition of (a) knee flexion angle (sagittal plane) (b) hip rotation angle (transverse plane). RASI: right anterior superior iliac spine; LASI: Left anterior superior iliac spine
Figure 8. Participant flow diagram
Figure 9. Impact severity measurements as a function of group × time of (a) normalized hip impact force (b) hip impact velocity (c) hip impact acceleration (d) head acceleration
Figure 10. Impact severity parameters as a function of falling-side × group. (a) Normalize hip impact force at T2 (b) Normalized hip impact force at T3_{retention} (c) Hip impact velocity at T2 (d) Hip impact velocity at T3_{retention} (e) Hip impact acceleration at T2 (f) Hip impact acceleration at T3_{retention} (g) Head acceleration at T2 (h) Head acceleration at T3_{retention}
Figure 11. Joint kinematics as a function of group × time of (a) knee angle (b) hip angle
Figure 12. Scatter plots of analyzed relationships between knee flexion angle and (a) normalized hip impact force (b) hip impact velocity (c) hip impact acceleration (d) head acceleration
REFERENCES


54. Centers for Disease Control and Prevention, C., Unintentional fall death rates, Adults 65+. 2014: Atlanta, GA.
ABSTRACT

Objective: To systematically synthesize information on safe landing strategies for a fall and quantitatively examine the effects of the strategies to reduce risk of injury from a fall.

Data Sources: PubMed, Web of Science, Cumulative Index to Nursing and Allied Health Literature, and Cochrane Library

Study Selection: Databases were searched using the combinations of keywords of “falls”, “strategy”, “impact” and “load”. Randomized control trials, cohort studies, pre-post studies, or cross-sectional studies were included.

Data Extraction: The fall strategies were extracted and categorized by falling direction. Measurements of impact loads that reflect the risk of injuries were extracted (e.g. impact velocity, impact force, fall duration, and impact angle). Hedges g was used as effect size to quantify effect of a protective landing strategy to reduce the impact load.

Data Synthesis: A total of seven landing strategies (squatting, elbow flexion, forward rotation, martial arts rolling, martial arts slapping, relaxed muscle, and stepping) in 13 studies were examined. In general, all strategies, except for the martial arts slapping technique, significantly reduced impact load (g’s=0.73 to 2.70). Squatting was an efficient strategy to reduce impact in backward falling (g=1.77) while elbow flexion with outstretched arms was effective in forward falling (g=0.82). Also, in sideways falling strategies, martial arts rolling (g=2.70) and forward rotation (g=0.82) were the most efficient strategies to reduce impact load.

Conclusions: The result showed that landing strategies have significant effect on reducing
impact load during a fall and might be effective to reduce impact load of falling. The current study also highlighted limitations of the previous studies which focused on a young population and self-initiated falls. Further investigation with elderly individuals and unexpected falls is necessary to verify effectiveness and suitableness of the strategies to at-risk population in real-life falls.

Key words: Falls; Impact; Strategy; Injury

Abbreviations: Cumulative Index to Nursing and Allied Health Literature, CINAHL; effect size, ES; martial arts, MA; randomized control trial, RCT;

1. INTRODUCTION

A fall is an unexpected event in which an individual comes to rest on the ground floor or lower level [1]. They are one of the leading causes of injury and death among the elderly [2]. An estimated 40% of community-dwelling people aged over 65 years fall at least once a year, and nearly 15% fall twice or more per year [3]. Falls result in 62.5% (2.5 million) of non-fatal injuries of older adults in the United States that require treatment in emergency departments and hospitalization [4]. The direct medical cost for fall related injuries reaches $19 billion annually in the U.S. alone [5]. In addition, as the population ages, the number of annual fall related injuries in the United States is expected to increase to 5.7 million by the year 2030 [6]. Given the frequency of falls and the severity of fall related injuries, insights are clearly necessary to decrease the risk of injury from falls.

Injury prevention efforts have been mainly targeted intrinsic (e.g. muscle weakness, balance problem, cognitive function) or extrinsic (e.g. environmental hazards, assistive devices) fall risk factors [7]. For example, fall prevention programs often consist of recommendations on environmental modification (e.g. improving lighting, installing handrails), behavioral education
(e.g. not hurrying while walking, using a mobility device), and exercise training (e.g. muscle strengthening, tai-chi) [8]. Exercise interventions are one of the most efficient approaches to reduce fall risk as it can significantly improve physiological capacity for balance and reduced monthly rate of falling in older adults [8]. It is important to note that despite the benefits of targeted exercise training, participants within these program still fall [7, 9].

An alternative approach that rehabilitation specialists could implement is to teach individuals how to fall in such a manner to reduce injury. It has been speculated that there are unique protective movements which enable safe landing during a fall [10]. However, the efficiency and mechanisms of the protective movement strategies have received relatively little attention.

A few studies have suggested that safe landing strategies may be effective in reducing the risk of injury from falling. The risk of injury has been quantified by various biomechanical parameters (e.g. force, velocity) that reflect magnitude of loads applied to the body at impact (i.e. impact severity). Also the types of strategies are based on the falling direction and the part of body being protected. For example, martial arts (MA) fall techniques, characterized by rolling movements of the trunk, have been observed to efficiently protect the hips in sideways fall [11]. A narrative review in 2003 summarized landing strategies to reduce loading on upper extremity when falling [12]. Based on the available evidence, it concluded that the elbow flexion in forward fall can significantly reduce impact force applied to the wrist. Although an important step in synthesizing the data, it focused only on upper extremity injury and provided minimal information concerning falls in non-forward directions (e.g. sideways falls).

In the past decade, landing strategies to reduce the impact severity have been further investigated and sufficient amount of evidence of their effect has been gained allowing for quantitative synthesis of information. The effects of safe landing strategies to reduce risk of fall-
related injury is seemingly associated with multiple factors including the location of impact, direction of falling, and magnitude of loads applied to the body at impact [13]. Therefore, the purpose of this review is to systematically synthesize information on safe landing strategies and quantitatively examine the effects of the strategies via meta-analysis.

2. METHODS

2.1. Study selection criteria

Studies that met all of the following criteria were included in the review – study design: randomized control trial (RCT), cohort study, pre-post study, or cross-sectional study; subject: human; main outcome: kinetic or kinematic impact severity measurements including impact velocity, impact force, fall duration, impact angle; and language: English. Studies were excluded from the review if they met one or more of the following exclusion criteria: 1) only computer simulation; 2) non-experimental design (questionnaire study); 3) a study without (did not include) kinetic or kinematic impact severity measurement; 4) fall simulation without ground impact; 5) a study without comparative responses of falling strategy; 6) non-English publication; 7) review paper or case study; and 8) non-peer reviewed article (e.g., dissertation or conference proceeding).

2.2. Search strategy

The systematic review protocol described in the Preferred Reporting Items for Systemic Reviews and Meta-Analysis statement [14] were adopted to guide the review process. The search retrieved articles from 1980 and continued until January 2016.

Keyword search was performed in PubMed, Web of science, Cumulative Index to Nursing and Allied Health Literature (CINAHL), and Cochrane Library. The search algorithm included all
possible combinations of keywords (with wildcard characters) from the following four groups: (1) fall OR falls OR "sideways falls" OR "lateral falls" OR "forward falls" OR "backward falls" (2) technique* OR training OR strategy* OR protective OR response* OR reflex (3) “femoral fracture” OR “hip fracture” OR “hip impact” OR “wrist fracture” OR osteoporosis OR “bone fracture” and (4) biomechanic* OR kinematic* OR kinetic* OR EMG OR “muscle activation” OR velocity OR force. Both authors (Y.M, J.S.) independently assessed titles and abstracts of the identified articles to determine whether or not the articles were eligible. Full-text articles were obtained when either reviewer decided that the article potentially fulfilled the inclusion criteria.

We also conducted a cited reference search (i.e., forward reference search) and a reference list search (i.e., backward reference search) based on the articles meeting the study selection criteria that were identified from keyword search. Articles identified through forward/backward reference search were further screened and evaluated using the same study selection criteria. We repeated the reference search on all newly-identified articles until no additional relevant articles were found.

2.3. Data extraction

A standardized data extraction form was used to collect the following methodological and outcome variables from each included study: author(s), publication year, study design, protective landing strategy, comparative normal landing strategy, fall simulation method (i.e., self-initiated vs. unexpected fall, standing vs. kneeling fall, direction of falls, instruction of landing strategy), impact body part, sample size, participant demographics (i.e., gender, age, height, weight), and impact severity outcome (i.e., impact velocity, impact kinetic energy, impact force, fall duration, and impact angle). Impact velocity was defined as the velocity of the body part just prior to impact[13]. Impact kinetic energy was defined as \( \frac{1}{2}mv^2 \) where \( m \) is an anthropometric mass of
the body part and $v$ is the impact velocity[13]. Impact force was defined as the initial peak force in the vertical direction at impact[11]. Fall duration was defined as the time between fall initiation and initial impact[15]. Impact angle indicated how close the individual came to directly impacting the lateral side of the pelvis (or greater trochanter of the proximal femur)[16]. 0 degree reflected direct impact to the lateral aspect of the pelvis, and +/-90 degree reflected impact to the buttocks or anterior aspect of the pelvis[16].

2.4. Quantitative data synthesis

For a protective fall strategy included in more than two papers, meta-analysis was performed to estimate the pooled effect size (ES) of the effect of landing strategy. In the present study, measure of Hedges $g$ was obtained as ES and used to quantify difference of impact severity between a protective landing strategy and a normal landing strategy. Conventionally, $g$ values of 0.2, 0.5 and 0.8 are considered to represent small, medium and large effects, respectively. A random-effect model was estimated given a $P$-value less than 0.05 from the Cochran’s Q test or an $I^2$ statistics at or above 50%; otherwise, a fixed-effect model was estimated.

Publication bias was assessed by the Egger’s test. Publication bias occurs when the results of published studies are not representative of results of all completed studies [17]. All statistical analyses were conducted using Stata 14.0 SE version. All analyses used one-sided tests based on the hypothesis that landing strategies reduces impact severity, and $P$-values equal or less than 0.05 were considered statistically significant. Forest plots were generated using Review Manager software.

2.5. Study quality assessment
Study quality was assessed by the following criteria [17]. (1) Was the research question clearly stated? (2) Were the inclusion and exclusion criteria clearly stated? (3) Were the protective landing strategy and comparative strategy clearly stated? (4) Were the main findings of the study clearly described? (5) Did the selected parameters indicate impact severity? (6) Was the definition of initial impact well described? (7) Was the fall simulation condition clearly stated and uniformly applied to all participants? (8) Was the fall simulation protocol appropriate to reflect real-life fall situation? (9) Was a sample size justification via power analysis provided? (10) Were potential confounders properly controlled in the analysis? Both authors (Y.M., J.S.) independently scored each study based on these 10 criteria, with disagreement resolved through discussion. Scores for each criterion range from 0 to 2, depending on whether the criterion was unmentioned or unmet (0), partially met (1), or completely met (2). The possible total study score ranges between 0 and 20. Study quality score helped measure the strength of study evidence, but was not used to determine the inclusion of studies.

3. RESULTS

3.1. Study selection

As Figure 13 shows, a total of 380 unduplicated articles were identified through keyword and reference search. 354 of them were excluded in title and abstract screening. The remaining 26 articles were reviewed in full texts, and 13 of them were excluded for not meeting the study selection criteria as listed in Figure 13. Finally, the remaining 13 articles [11, 13, 15, 16, 18-26] were included in the review.

3.2. Basic characteristics of selected studies
Basic characteristics of selected studies are summarized in Table 4. There were 11 pre-post studies and two cohort studies. Overall, 60% of the participants were female. There were 5 studies that recruited females only and 3 studies that recruited males only. Average age was under 30 years old in 12 out of 13 studies (average: 28.0 +/- 13.2 yrs, range: 21-28.3 yrs). Only one study investigated individuals over 65 old (average: 69.5 +/- 5.9 yrs).

6 papers (46%) utilized self-initiated falls from a kneeling position while 2 studies (15%) examined self-initiated falls from a standing position. There were 4 studies (31%) that utilized tether release from a standing position. Among them, one study informed participants of the timing of tether release while the remaining 3 released it unexpectedly. One paper used unexpected translation of a surface in standing position to induce a fall.

The most frequently reported impact severity parameters were impact velocity (10 studies, 77%) and impact force (7 studies, 54%). In addition, three studies (23%) reported impact angle of the trunk, two studies (13%) reported fall duration and two studies (13%) utilized impact kinetic energy as impact severity parameters.

3.3. Fall strategies based on falling directions

Figure 14 demonstrates the types of safe landing strategies and comparative strategies based on falling direction. 9 studies (69%) investigated falls to the side. Among the side-fall studies, the effect of martial arts (MA) technique such as a judo fall has been investigated in the greatest number of reports (5 papers). Two studies investigated the influence of muscle relaxation and one study examined the influence of stepping prior to impact. Also there was one study that compared the influence of forward rotation of the trunk to that of backward rotation. All of the studies examined impact severity at the hip.
There were 2 studies (15%) that investigated falling in a backward direction. Both studies examined effect of squat motion on diminishing impact severity at the hip and wrist. Two studies (15%) examined falls in a forward direction. Both studies investigated the effect of elbow flexion when impacting the ground with outstretched hands. The studies investigated impact severity at the elbow, shoulder, wrist and neck.

3.4. Meta-analysis on falling strategy

MA rolling and MA slapping strategies have been reported in a sufficient number of papers to conduct meta-analysis. Figure 15 demonstrates the forest plots of each meta-analysis. Overall, the reported effect sizes were heterogeneous in all parameters of all strategies except impact angle of MA rolling technique. All parameters in MA rolling have significant effect sizes (Ps ≤ 0.05) but effect sizes were not significant for any parameters in MA slapping (Ps > 0.05).

3.5. Effect of safe falling strategy

Table 5 summarized the effect of safe falling strategies. In the backward fall investigations, it was reported that a squatting strategy can reduce impact velocity of the wrist by 11% (g=1.09) and the hip by 18% (g=1.97). Also the squatting significantly reduced impact energy of the hip by 44% (g=1.77). Squatting also significantly shortened the fall duration from the initiation of a fall to the ground of the wrist (14%, g=1.73).

In the forward fall investigations, there was a significant effect of elbow flexion strategy on reducing impact force of the elbow by 40% (g=0.43), the shoulder by 26% (g=0.90), the wrist by 26% (g=0.82) and the hand by 14% (g=0.55). However, impact velocity of the neck was not influenced by the elbow flexion strategy.
Figure 16 displayed effect sizes of the sideway fall strategies. Forward rotation exhibited the largest effect size on reducing hip impact velocity followed by stepping strategy, MA rolling, and relaxed muscle strategy. Also forward rotation significantly diminished impact energy on hip by 34% ($g=1.00$).

MA rolling was the only strategy that significantly decreased hip impact force (25% reduction, $g=2.70$). MA rolling and relaxed muscle strategies both reduced impact angle of the trunk (i.e. less vertical) by approximately 60% (MA rolling: $g=1.33$, relaxed muscle: $g=0.73$). Also, the stepping strategy significantly increased fall duration by 13% ($g=1.56$) while MA rolling did not have influence on fall duration.

MA slapping did not have significant influence on any of reported impact severity parameters. Egger’s test indicates none of the strategies has publication bias ($P>0.05$).

3.6. Study quality assessment

Table 6 reports results of study quality assessment. Studies included in the review on average scored 13.5 out of 20 and ranged between 8 and 18. The distribution of qualification differed substantially across criteria. 7 out of 13 studies included in the review clearly described their main findings, properly described a protective landing strategy and a controlled strategy, uniformly applied fall simulation to all participants, and clearly indicated potential confounders [13, 15, 16, 21-23, 25]. In contrast, only one study provided sample size justification [15] and only two studies clearly stated inclusion and exclusion criteria [15, 25].

4. DISCUSSION
Falls are one of the most frequent causes of injury related morbidity and mortality among the elderly [2]. It is noted that 40% of individuals over 65 years old fall each year and 30% of those falls cause moderate to severe injuries [27]. Given the adverse consequence of falls, a significant amount of scientific inquiry has focused on their prevention [9]. In contrast, considerably less attention has been paid to strategies of safe landing (i.e. falling without being injured). It has been proposed that natural responses to falls by older adults may not optimally reduce injury risk [24]. Consequently, over the past two decades, researchers have attempted to examine efficiency of safe landing strategies to reduce impact severity of falls.

The current review provides a comprehensive understanding of safe landing strategies and their unique contributions on reducing impact severity. In addition, it also illustrates the gaps in the current literature. A total of seven landing strategies (squatting, elbow flexion, forward rotation, MA rolling, MA slapping, relaxed muscle, and stepping) in 13 investigations encompassing 219 individuals were examined. The results show all of the strategies except MA slapping have significant effect on reducing impact severity when implemented during a fall.

The results indicated that each strategy has distinctive advantages on reducing impact severity. Squatting and elbow flexion reduce impact velocity and force through absorption of energy in the eccentrically contracting muscles of the lower and upper extremities [13, 20]. Therefore, sufficient muscle strength of the extremities is essential to maximize efficiency of these strategies. Also a few strategies enhance energy distribution by increasing the contact area of the body. Specifically, while sideways falling has high risk of direct contact of the proximal femur, forward rotation leads to landing on the knees, hands, and pelvis nearly simultaneously. This approach spreads out the impact energy across the location and results in a reduction of impact severity [25, 26]. Also MA rolling induces optimal distribution of the impact force applied to body part along the contact path.
while rolling [24].

In addition to the dynamic aspect of impact severity, change of loading configuration could also reduce risk of injury. The result indicated that MA rolling and relaxed muscles result in less vertical trunk angle at impact and reduce energy absorbed by hip [22]. On the other hand, a few strategies enable better preparation for safe landing. The stepping strategy increases fall duration, consequently allowing for enough time to adjust and avoid injuries. For instance even unsuccessful attempts to recover balance through stepping was observed to be beneficial in reducing impact severity [16]. Also, forward rotation during a sideways fall not only dissipates impact energy but also allows subjects to coordinate their movement through visualization of the landing surface prior to impact [25]. Lastly, although MA slapping does not show any difference in impact severity, it was reported that the strategy is essential to maintain stability during MA rolling [22]. An appropriate technique should be selected considering the unique benefits of each landing strategy.

It has been speculated that elderly individuals have altered response of falling that leads to increased risk of injury [28, 29]. The benefit of the techniques depends on muscle strength and early initiation of the techniques [13, 29]. However, older individuals might have a diminished ability to perform the protective strategies due to reduced muscle strength, delayed reaction time and belated detection of imbalance [12, 29]. Further examination on influence of aging on the efficiency of strategies is warranted.

The current review classified strategies based on the direction of falls. Since the direction of a fall influences the part of the body that impacts the ground, an appropriate strategy should be selected based on the falling direction[12]. Given that falling to the side has a 6-fold greater risk for hip fracture than forward or backward falls [30], they have been the focus of the majority of research.
Although previous literature has documented distinctive benefits between safe landing strategies, several limitations have been observed. It is notable that only one study included elderly subjects, while the majority of studies were conducted with young healthy subjects. Consequently, it is debatable whether these fall techniques would be both effective and suitable for the older adults. For instance, although the martial arts rolling may be an effective strategy, it may not be practical to teach this technique to individuals at risk of falls. It is important to note that some protective responses have associated risks that might lead to adverse consequence when performed inappropriately. For example, elbow flexion might increase the risk of head impact as the distance between the head and ground decreases with this strategy [29]. Also although squatting reduces impact velocity, it significantly decreases fall duration reducing the time to prepare for safe landing [28]. Further investigations on the strategies with older adults and clinical populations are essential to generalize effectiveness of the fall techniques to at risk population.

Various parameters were utilized to represent fall severity. Impact velocity, force, and energy represent the external load at impact while trunk angle reflects body configuration at impact and falling duration indicates time course of the fall[12]. While impact velocity has been utilized the most, it was observed that impact velocity does not always reflect impact force which is a direct indication of external load [24]. It was suggested that when impact force measurements are not possible for a safety reason, it is more appropriate to combine impact velocity with energy estimates [24].

Also, it is not clear whether the reductions in impact severity parameters are clinically meaningful. Fracture risk not only depends on the external load applied on the body, but also on the load necessary to cause a fracture [19]. Therefore, it is not clear whether the observed reduction of fall severity in young adults is sufficient to minimize injury in individuals who may have
diminished bone density and tissue tolerance. Additionally, while backward falling is reported to be the leading cause of traumatic brain injury [31], risk of head injury has been neglected in fall severity measurements. Therefore, such parameters are warranted to be included to provide a more valid evidence of clinical significance of the strategies.

Lastly, falls performed in the previous studies differ in some aspects from most falls in daily life. For safety reasons, majority of studies utilized self-initiated falls or falls from kneeling height. However, most falls in real life are caused by sudden loss of balance due to an unexpected slip or trip, or loss of stability [13]. It is possible that protective responses in self-initiated falls were governed by motor plans selected before fall initiation [10]. In addition, the activity of the faller at the time of imbalance such as reaching, bending, walking, rising, or turning may influence ability to modulate impact severity through the strategies [13]. Recently, there was an attempt to overcome the bias of lab-based falls by analyzing real life falls captured by video footage in long-term care facilities [32]. The investigation described that real-life falling had a 16% lower pelvis impact velocity than lab-based ones supporting a discrepancy between methodological approaches [32]. Consequently, it is promising to further utilize innovative experimental design that could reflect real life falling in a safe manner.

The current meta-analysis has a few limitations. First, because of the small number of studies on a given landing strategy, meta-analysis was only available for a limited number. Therefore, further examinations on each landing strategy are necessary. Additionally, heterogeneity of impact severity metrics further prevented synthesizing information regarding the effect of landing strategies. Thus, it is necessary to identify the gold-standard of impact severity metrics to examine risk of injury of falling. Lastly, most studies had small and/or unrepresentative samples, which
compromised generalizability of study findings.

5. CONCLUSION

In conclusion, this study systemically reviewed and quantitatively synthesized findings from existing studies on safe landing strategies. The result showed that all of the strategies except MA slapping have a significant effect on reducing the impact severity of various falls. An appropriate technique should be selected based on falling direction and individual capacity. Further investigation with elderly individuals is necessary to verify effectiveness and suitableness of the strategies to at-risk populations. Also, to ensure more valid evidence of the benefits of the strategies, severity parameters reflecting practical fracture risk should be added and innovative methods to simulate real-life falls need to be designed.
## TABLES

### Table 4. Basic Characteristics of the studies

<table>
<thead>
<tr>
<th>Author(year)/study design</th>
<th>Fall direction</th>
<th>Safe landing strategy</th>
<th>Subjects</th>
<th>Fall simulation method</th>
<th>Impact part / Impact severity parameter</th>
<th>Fall strategy instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tan (2006) / PP</td>
<td>Backward</td>
<td>Squatting</td>
<td>N=12 (F=9); Age = 27.6±10.7 yrs</td>
<td>Unexpected tether release in standing position</td>
<td>Wrist/Impact velocity; Fall duration</td>
<td>Participants performed backward fall with knee flexed. They were instructed to land as softly as possible and reduce impact to the hips</td>
</tr>
<tr>
<td>Robinovitch (2004) / PP</td>
<td>Backward</td>
<td>Squatting</td>
<td>N=23 (F=23); Age = 24+/-5 yrs</td>
<td>Unexpected tether release in standing position</td>
<td>Hip/Impact velocity; Impact kinetic energy</td>
<td>&quot;Squatting during descend&quot; did not mean to simply collapse the knees and hip into full flexion during descent, but rather to flex the knees and hips while contracting the muscles spanning these joints, as is done to slow the speed of descent during sitting</td>
</tr>
<tr>
<td>Chou (2001) / PP</td>
<td>Forward</td>
<td>Elbow Flexion</td>
<td>N=11(F=0); Age=26.1+/-2.6 yrs</td>
<td>Self-initiated fall in standing position</td>
<td>Elbow; Shoulder; Wrist/Impact force</td>
<td>Subjects were asked to spontaneously flex the elbow after the moment of impact. This action was very similar to a flexion motion during a push-up.</td>
</tr>
<tr>
<td>Lo (2003) / RCT</td>
<td>Forward</td>
<td>Elbow Flexion</td>
<td>N=29(F=0); Age=23+/-3 yrs</td>
<td>Expected tether release in standing position</td>
<td>Wrist; Neck/Impact force; Impact velocity</td>
<td>Reduce your elbow extension speed prior to hand-ground impact; avoid acceleration of your hand into the ground at impact-just hold it steady and wait for the ground to hit it; Land with a slightly flexed elbow angle; do not ever land with a straight elbow; attempt to catch the ground;</td>
</tr>
<tr>
<td>Robinovitch (2003) / PP</td>
<td>Side</td>
<td>Forward/Backward Rotation</td>
<td>N=22(F=22); Age=23+/-5 yrs</td>
<td>Unexpected tether release in standing position</td>
<td>Hip/Impact velocity; Impact kinetic energy</td>
<td>Participants were instructed to &quot;land as softly as possible&quot; and to &quot;avoid impacting the hip or side of the thigh during the fall&quot;. Also the participants were instructed to either rotate forward during descent to land on the outstretched hands or to rotate backward during descent to land on the buttocks. Finally, we instructed the subjects to keep their knees extended during descent.</td>
</tr>
</tbody>
</table>
(Table 4 continued)

<table>
<thead>
<tr>
<th>Author(year)/study design</th>
<th>Fall direction</th>
<th>Safe landing strategy</th>
<th>Subjects</th>
<th>Fall simulation method</th>
<th>Impact part / severity parameter</th>
<th>Fall strategy instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groen (2007) / PP</td>
<td>Side</td>
<td>Martial arts fall (Rolling &amp; Slapping)</td>
<td>N=11(F=0); Age=24.2+/-.3 yrs</td>
<td>Self-initiated fall in kneeling position</td>
<td>Hip/Impact force; Impact velocity; Impact angle</td>
<td>The Martial Arts technique is derived from Judo. The fall is changed into a rolling movement, which allows for an optimal distribution of impact applied to any site along the contact path. In slapping condition, the arm is used to break the fall.</td>
</tr>
<tr>
<td>van der Zijden (2012) / PP</td>
<td>Side</td>
<td>Martial arts fall</td>
<td>N=12(F=3); Age=27.6+/-.10.7 yrs</td>
<td>Self-initiated fall in kneeling position</td>
<td>Hip/Impact force; Impact angle</td>
<td>Followed method of Groen 2007</td>
</tr>
<tr>
<td>Weerdesteyn (2008) / PP</td>
<td>Side</td>
<td>Martial arts fall (Rolling &amp; Slapping)</td>
<td>N=10(F=10); Age=28.3+/-.6.6 yrs</td>
<td>Self-initiated fall in kneeling position</td>
<td>Wrist/Impact force</td>
<td>A sideways martial arts technique is characterized by trunk lateral flexion and rotation and shoulder protraction in order to enable rolling on after impact. This allows for an optimal distribution of impact applied to any site along the contact path. In addition, arms can be slapped on the ground after hip and trunk impact.</td>
</tr>
<tr>
<td>Groen (2010) / PP</td>
<td>Side</td>
<td>Martial arts fall (Rolling &amp; Slapping)</td>
<td>N=25(F=19); Age=69.5+/-.5.9 yrs</td>
<td>Self-initiated fall in kneeling position</td>
<td>Hip/Impact force; Impact velocity; Fall duration</td>
<td>Followed method of Groen 2007</td>
</tr>
<tr>
<td>Sabick (1999) / PP</td>
<td>Side</td>
<td>Relaxed muscle, Slap</td>
<td>N=9(F=2); Age=NR</td>
<td>Self-initiated fall in kneeling position</td>
<td>Hip/Impact force; Impact velocity</td>
<td>The subject was told to fall with his body &quot;as relaxed as possible&quot;. Also the participants were instructed to perform a slap fall</td>
</tr>
</tbody>
</table>
## Table 4 continued

<table>
<thead>
<tr>
<th>Study</th>
<th>Side</th>
<th>Muscle Activity</th>
<th>Sample Size</th>
<th>Fall Initiation</th>
<th>Fall Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Van den Kroonenberg (1996) / PP</td>
<td>Side</td>
<td>Relaxed muscle</td>
<td>N=6(F=NR); Age=23.7 +/- 3.67 yrs</td>
<td>Self-initiated fall in standing position</td>
<td>Hip/Impact velocity; Impact angle</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>Feldman (2007) / Cohort</td>
<td>Side</td>
<td>Stepping</td>
<td>N=44(F=31); Age=21 +/- 2 yrs</td>
<td>Unexpected translation of surface in standing position</td>
<td>Hip/ Fall duration; Impact velocity</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

To investigate the effect of muscle activity on fall dynamics, the subjects were instructed either to fall as relaxed as they could, almost as if they had fainted, or, in another series, to fall naturally, using the musculature of their lower extremity as they would in a 'normal' reflex-mediated fall.

The study classified a trial as involving a "complete step", if there was lifting and repositioning of the left (loaded) foot in a more lateral position on the ground, or the right (unloaded) foot in a more medial location, before impact to a hand, knee, or the pelvis.

Note: PP=Pre-post study; randomized control trial, RCT;
### Table 5. Quantitative effect of protective strategies

<table>
<thead>
<tr>
<th>Fall direction</th>
<th>Safe landing strategy</th>
<th>Impact part</th>
<th>Severity parameter</th>
<th>Statistical result</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Backward</strong></td>
<td>Squatting vs no-squatting</td>
<td>Wrist</td>
<td>Impact velocity</td>
<td>Significantly ↓ (2.27 +/- 0.30 m/s to 2.01 +/- 0.13 m/s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fall duration</td>
<td></td>
<td>Significantly ↓ (873 +/- 67 ms to 749 +/- 72 ms)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hip</td>
<td>Impact velocity</td>
<td>Significantly ↓ (3.3 +/- 0.3 m/s to 2.7 +/- 0.3 m/s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Impact Energy</td>
<td>Significantly ↓ (307 +/- 90 J to 172 +/- 56 J)</td>
</tr>
<tr>
<td><strong>Forward</strong></td>
<td>Elbow flexion vs Hand extension when catching the ground</td>
<td>Hand</td>
<td>Impact force</td>
<td>Significantly ↓ (880 +/- 40 N to 745 +/- 42 N)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wrist</td>
<td>Impact force</td>
<td>Significantly ↓ (11.2 +/- 3.6 N/kg.g to 8.2 +/- 3.4 N/kg.g)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Elbow</td>
<td>Impact force</td>
<td>Significantly ↓ (2.66 +/- 0.21 m/s to 2.52 +/- 0.15 m/s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shoulder</td>
<td>Impact force</td>
<td>Significantly ↓ (32.6 +/- 6.5 N/kg.g to 24.1 +/- 11 N/kg.g)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Neck</td>
<td>Impact velocity</td>
<td>Not significantly different (2.69 +/- 0.25 m/s vs 2.68 +/- 0.24 m/s)</td>
</tr>
<tr>
<td><strong>Side</strong></td>
<td>Forward rotation vs backward rotation</td>
<td>Hip</td>
<td>Impact velocity</td>
<td>Significantly ↓ in forward rotation (2.95 +/- 0.25 m/s to 2.45 +/- 0.77 m/s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact Energy</td>
<td></td>
<td>Significantly ↓ in forward rotation (238 +/- 70 J to 156 +/- 90 J)</td>
</tr>
<tr>
<td></td>
<td>MA Rolling vs Hip blocking fall</td>
<td>Fall duration</td>
<td></td>
<td>Not significantly different (246 +/- 92 ms vs 235 +/- 72 ms)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact force</td>
<td></td>
<td>Significantly ↓ in 5 out of 5 papers (Values are provided at Fig 3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact velocity</td>
<td></td>
<td>Significantly ↓ in 3 out of 4 papers (Values are provided at Fig 3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact angle</td>
<td></td>
<td>Significantly less vertical in 2 out of 2 papers (Values are provided at Fig 3)</td>
</tr>
<tr>
<td><strong>Relaxed muscle</strong> vs no-slap when performing Martial arts fall</td>
<td>Hip</td>
<td>Impact force</td>
<td>Not significantly different in 2 out of 3 papers (Values are provided at Fig 3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact velocity</td>
<td></td>
<td>Not significantly different in 2 out of 2 papers (Values are provided at Fig 3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact angle</td>
<td></td>
<td>Not significantly different (17 +/- 5 degree vs 15 +/- 4 degree)</td>
</tr>
<tr>
<td><strong>Stepping</strong></td>
<td>vs non-stepping before falling</td>
<td>Hip</td>
<td>Impact force</td>
<td>Not significantly different (2.76 +/- 0.83 N/kg.g and 2.69 +/- 0.68 N/kg.g)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact velocity</td>
<td></td>
<td>Significantly ↓ (3.31 +/- 0.43 m/s to 3.09 +/- 0.41 m/s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact angle</td>
<td></td>
<td>Significantly less vertical (13.6 +/- 11.2 degree to 21.8 +/- 10.4 degree)</td>
</tr>
</tbody>
</table>

**Note:** MA=martial arts; ↓=reduced; ↑=increased
### Table 6. Study quality assessment

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Was the research question clearly stated?</td>
<td>1.9</td>
<td>0.3</td>
</tr>
<tr>
<td>2. Were the inclusion and exclusion criteria clearly stated?</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>3. Were the protective landing strategy and comparative strategy clearly stated?</td>
<td>1.9</td>
<td>0.3</td>
</tr>
<tr>
<td>4. Were the main findings of the study clearly described?</td>
<td>1.9</td>
<td>0.3</td>
</tr>
<tr>
<td>5. Did the selected parameters indicate impact severity?</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>6. Was definition of initial impact well described?</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td>7. Was fall simulation condition clearly stated and uniformly applied to all participants?</td>
<td>1.8</td>
<td>0.4</td>
</tr>
<tr>
<td>8. Was fall simulation protocol appropriate to reflect real-life fall situation?</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>9. Was a sample size justification via power analysis provided?</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>10. Were potential confounders (age, gender, height, weight) properly described in the analysis?</td>
<td>1.6</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Total score</strong></td>
<td><strong>13.5</strong></td>
<td><strong>2.7</strong></td>
</tr>
</tbody>
</table>

Notes: Scores for each criterion range from 0 to 2, depending on whether the criterion was unmentioned or unmet (0), partially met (1), or completely met (2). The total study score ranges between 0 and 20.
Figure 13. Flow chart of study selection
<table>
<thead>
<tr>
<th>Fall direction</th>
<th>Safe landing technique</th>
<th>Comparative technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backward</td>
<td>Squatting: Flex the knees and hips while contracting the muscles spanning these joints.</td>
<td>No squatting: Fall backward with the extended knee.</td>
</tr>
<tr>
<td>Forward</td>
<td>Elbow Flexion: Catch the ground with the outstretched arms while landing with the slightly flexed elbow.</td>
<td>Elbow extension: Catch the ground with outstretched arms while landing with the extended elbow.</td>
</tr>
<tr>
<td>Side</td>
<td>Forward Rotation: Rotate forward during the descent to land on the outstretched hands.</td>
<td>Backward Rotation: Rotate backward during the descent to land on the buttocks.</td>
</tr>
<tr>
<td></td>
<td>Martial arts rolling: Flex knee during the decent, flex trunk laterally and rotate slightly backward to facilitate rolling away from the impact point.</td>
<td>Block fall: Stretch out the arm into the direction of the impending fall while laterally flexing the trunk.</td>
</tr>
<tr>
<td></td>
<td>Martial arts slapping: Slap the arm on the falling side on the ground after the impact of MA rolling.</td>
<td>Martial arts no slapping: Facilitate MA rolling without contacting the ground with the arms.</td>
</tr>
<tr>
<td></td>
<td>Stepping: Reposition the foot in a more lateral position during the decent.</td>
<td>No stepping: Stay the foot in the same position during the decent.</td>
</tr>
<tr>
<td></td>
<td>Relaxed muscle: Fall with the body as relaxed as possible without resisting against to the fall</td>
<td>Non-relaxed muscle: Fall with the tensed muscles of the body.</td>
</tr>
</tbody>
</table>

**Figure 14.** Schematic representation of safe landing techniques and comparative techniques
Figure 15. Forest plots of effect of (a) martial arts (MA) rolling (b) MA slapping to reduce impact severity. Standard mean difference was calculated by Hedge’s g effect size.
Figure 16. Effect sizes (Hedges g) of side-way safe landing strategies. NS = non-significant effect size
REFERENCES


