Archives of Physical Medicine and Rehabilitation

journal homepage: www.archives-pmr.org

Archives of Physical Medicine and Rehabilitation 2017;98:783-94

REVIEW ARTICLE (META-ANALYSIS)

Safe Landing Strategies During a Fall: Systematic Review and Meta-Analysis

Yaejin Moon, MSc, Jacob J. Sosnoff, PhD

From the Department of Kinesiology and Community Health, University of Illinois at Urbana-Champaign, Urbana, IL.

Abstract

Objectives: To systematically synthesize information on safe landing strategies for a fall, and quantitatively examine the effects of the strategies to reduce the 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 controlled trials, cohort studies, pre-post studies, and cross-sectional studies were included.

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

Data Synthesis: A total of 7 landing strategies (squatting, elbow flexion, forward rotation, martial arts rolling, martial arts slapping, relaxed muscle, stepping) in 13 studies were examined. In general, all strategies, except for the martial arts slapping technique, significantly reduced impact load (g values=.73−2.70). 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=.82). Also, in sideways falling strategies, martial arts rolling (g=2.70) and forward rotation (g=.82) were the most efficient strategies to reduce impact load.

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

Archives of Physical Medicine and Rehabilitation 2017;98:783-94

A fall is an unexpected event in which an individual comes to rest on the ground floor or lower level.[1] Falls are one of the leading causes of injury and death among the elderly.[2] An estimated 40% of community-dwelling people older than 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 nonfatal 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 United States 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 mainly targeted intrinsic (eg, muscle weakness, balance problem, cognitive function) or extrinsic (eg, environmental hazards, assistive devices) fall risk factors.[7] For example, fall prevention programs often consist of recommendations on environmental modification (eg, improving lighting, installing handrails), behavioral education (eg, not hurrying while walking, using a mobility device), and exercise training (eg, muscle strengthening, tai chi).[8] Exercise interventions are one of the most efficient approaches to reduce fall risk because they can significantly improve physiological capacity for balance and reduce the monthly rate of falling in older adults.[8] Despite the benefits of targeted exercise training, participants within these program still fall.[7,9]

Disclosures: J.J.S. reports grants from the National Multiple Sclerosis Society; the Consortium of Multiple Sclerosis Centers; MC10, Inc; and the National Institutes of Health. J.J.S. also reports personal fees from Third Bridge Consulting, outside the submitted work. The other author has nothing to disclose.

0003-9993/16/$36 - see front matter © 2016 by the American Congress of Rehabilitation Medicine
http://dx.doi.org/10.1016/j.apmr.2016.08.460

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 that 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 (eg, force, velocity) that reflect the magnitude of loads applied to the body at impact (ie, impact severity). Also, the types of strategies are based on the falling direction and the part of the 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 falls.[11] A narrative review[12] in 2003 summarized landing strategies to reduce loading on the upper extremity when falling. Based on the available evidence, it concluded that the elbow flexion strategy in forward fall can significantly reduce the impact force applied to the wrist. Although this review represents an important step in synthesizing the data, it focused only on upper extremity injury and provided minimal information concerning falls in nonforward directions (eg, sideway falls).

In the past decade, landing strategies to reduce the impact severity have been further investigated, and a sufficient amount of evidence of their effect has been gained, allowing for quantitative synthesis of information. The effects of safe landing strategies to reduce the risk of fall-related injury is seemingly associated with multiple factors including the location of impact, the direction of falling, and the 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.

Methods

Study selection criteria

Studies that met all of the following criteria were included in the review: (1) study design: randomized controlled trial, cohort study, prepost study, or cross-sectional study; (2) subject: human; (3) main outcome: kinetic or kinematic impact severity measurements including impact velocity, impact force, fall duration, and impact angle; and (4) language: English.

Studies were excluded from the review if they met 1 or more of the following exclusion criteria: (1) only a computer simulation; (2) nonexperimental design (questionnaire study); (3) a study without (did not include) kinetic or kinematic impact severity measurements; (4) fall simulation without ground impact; (5) a study without comparative responses of falling strategy; (6) non-English publication; (7) review article or case study; and (8) non−peer-reviewed article (eg, dissertation, conference proceeding).

Search strategy

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

A keyword search was performed in PubMed, Web of Science, Cumulative Index to Nursing and Allied Health Literature, and Cochrane Library. The search algorithm included all possible combinations of keywords (with wildcard characters) from the following 4 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. The search algorithm for each database is provided in appendix 1. Both authors (Y.M., J.J.S.) independently assessed titles and abstracts of the identified articles to determine whether 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 (ie, forward reference search) and a reference list search (ie, backward reference search) based on the articles meeting the study selection criteria that were identified from the 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.

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 (ie, self-initiated vs unexpected fall, standing vs kneeling fall, direction of falls, instruction of landing strategy), impact body part, sample size, participant demographics (ie, sex, age, height, weight), and impact severity outcome (ie, impact velocity, impact kinetic energy, impact force, fall duration, impact angle). Impact velocity was defined as the velocity of the body part just before 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] An angle of 0° reflected direct impact to the lateral aspect of the pelvis, and ±90° reflected impact to the buttocks or anterior aspect of the pelvis.[16]

Quantitative data synthesis

For a protective fall strategy included in more than 2 articles, meta-analysis was performed to estimate the pooled effect size of the effect of the landing strategy. In the present study, measure of Hedges' g was obtained as the effect size and used to quantify the 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 $<.05$ from the Cochran's Q test or an I^2 statistics $\geq 50\%$; otherwise, a fixed-effect model was estimated.

List of abbreviations:

MA martial arts

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.[a] All analyses used 1-sided tests based on the hypothesis that landing strategies reduce impact severity, and P values $\leq .05$ were considered statistically significant. Forest plots were generated using Review Manager software.[b]

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? and (10) Were potential confounders properly controlled in the analysis? Both authors (Y.M., J.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. The study quality score helped measure the strength of study evidence, but was not used to determine the inclusion of studies.

Results

Study selection

As figure 1 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 1. Finally, the remaining 13 articles[11,13,15,16,18-26] were included in the review.

Basic characteristics of selected studies

Basic characteristics of selected studies are summarized in table 1. There were 11 pre-post studies and 2 cohort studies. Overall, 60%

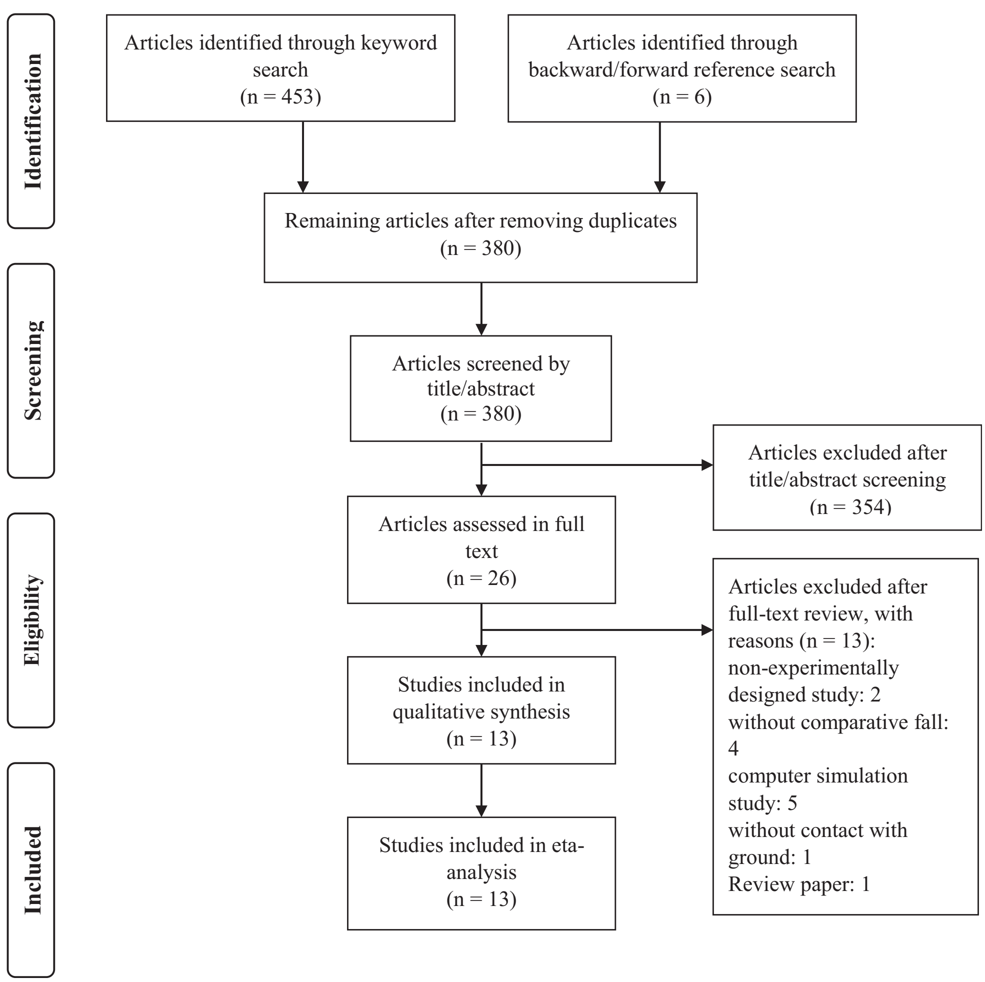

Fig 1 Flowchart of study selection.

of the participants were women. Five studies recruited women only, and 3 studies recruited men only. The average age was <30 years in 12 of 13 studies (average ± SD, 28.0±13.2y; range, 21−28.3y). Only 1 study investigated individuals aged >65 years (average ± SD, 69.5±5.9y).

Six articles (46%) used 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 used tether release from a standing position. Among them, 1 study informed participants of the timing of tether release, while the remaining 3 studies released it unexpectedly. One article 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, 3 studies (23%) reported impact angle of the trunk, 2 studies (13%) reported fall duration, and 2 studies (13%) used impact kinetic energy as impact severity parameters.

Fall strategies based on falling directions

Figure 2 demonstrates the types of safe landing strategies and comparative strategies based on falling direction. Nine studies (69%) investigated falls to the side. Among the side-fall studies, the effect of MA technique such as a judo fall has been investigated in the greatest number of reports (5 articles). Two studies investigated the influence of muscle relaxation, and 1 study examined the influence of stepping before impact. Also, there was 1 study that compared the influence of forward rotation of the trunk to that of backward rotation. All the studies examined impact severity at the hip.

There were 2 studies (15%) that investigated falling in a backward direction. Both studies examined the 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.

Meta-analysis on falling strategy

MA rolling and MA slapping strategies have been reported in a sufficient number of articles to conduct a meta-analysis. Figure 3 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 the MA rolling technique. All parameters in MA rolling have significant effect sizes (P values $\leq .05$), but effect sizes were not significant for any parameters in MA slapping (P values $>.05$).

Effect of safe falling strategy

Table 2 summarizes the effects 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 impact of the wrist (14%, $g=1.73$).

In the forward fall investigations, there was a significant effect of elbow flexion strategy on reducing the impact force of the elbow by 40% ($g=.43$), the shoulder by 26% ($g=.90$), the wrist by 26% ($g=.82$), and the hand by 14% ($g=.55$). However, impact velocity of the neck was not influenced by the elbow flexion strategy.

Figure 4 displays the effect sizes of the sideway fall strategies. Forward rotation exhibited the largest effect size on reducing hip impact velocity, followed by the stepping strategy, MA rolling, and the relaxed muscle strategy. Also, forward rotation significantly diminished impact energy on the 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 the impact angle of the trunk (ie, less vertical) by approximately 60% (MA rolling, $g=1.33$; relaxed muscle, $g=.73$). Also, the stepping strategy significantly increased fall duration by 13% ($g=1.56$), while MA rolling did not have an influence on fall duration. MA slapping did not have a significant influence on any of the reported impact severity parameters.

Egger's test indicates none of the strategies have publication bias ($P>.05$).

Study quality assessment

Table 3 reports the results of the 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. Seven 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 1 study provided sample size justification,[15] and only 2 studies clearly stated inclusion and exclusion criteria.[15,25]

Discussion

Falls are one of the most frequent causes of injury-related morbidity and mortality among the elderly.[2] Each year, 40% of individuals older than 65 years fall, 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 (ie, 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 2 decades, researchers have attempted to examine the efficiency of safe landing strategies to reduce the 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 7 landing strategies (squatting, elbow flexion, forward rotation, MA rolling, MA slapping, relaxed muscle, stepping) in 13 investigations encompassing 219 individuals were examined. The results show that all the strategies except MA slapping have a 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 the efficiency of these strategies. Also, a few strategies enhance energy distribution by increasing the contact area of the body. Specifically, while sideways falling has

Table 1 Basic characteristics of the studies

Author (Year)/ Study Design	Fall Direction	Safe Landing Strategy	Subjects	Fall Simulation Method	Impact Part/Impact Severity Parameter	Fall Strategy Instructions
Tan[26] (2006)/PP	Backward	Squatting	N=12 (F=9); Age: 27.6±10.7y	Unexpected tether release in standing position	Wrist/Impact velocity; Fall duration	Participants performed backward fall with knee flexed. They were instructed to land as softly as possible and reduce impact to the hips.
Robinovitch[13] (2004)/PP	Backward	Squatting	N=23 (F=23); Age: 24±5y	Unexpected tether release in standing position	Hip/Impact velocity; Impact kinetic energy	"Squatting during descend" 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.
Chou[20] (2001)/PP	Forward	Elbow flexion	N=11 (F=0); Age: 26.1±2.6y	Self-initiated fall in standing position	Elbow; Shoulder; Wrist/ Impact force	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.
Lo[23] (2003)/RCT	Forward	Elbow flexion	N=29 (F=0); Age: 23±3y	Expected tether release in standing position	Wrist; Neck/Impact force; Impact velocity	Reduce your elbow extension speed before 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.
Robinovitch[25] (2003)/PP	Side	Forward/backward rotation	N=22 (F=22); Age: 23±5y	Unexpected tether release in standing position	Hip/Impact velocity; Impact kinetic energy	Participants were instructed to "land as softly as possible" and to "avoid impacting the hip or side of the thigh during the fall." 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.
Groen[22] (2007)/PP	Side	MA fall (rolling and slapping)	N=11 (F=0); Age: 24.2±3.8y	Self-initiated fall in kneeling position	Hip/Impact force; Impact velocity; Impact angle	The MA 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.
van der Zijden[19] (2012)/PP	Side	MA fall	N=12 (F=3); Age: 27.6±10.7y	Self-initiated fall in kneeling position	Hip/Impact force; Impact angle	Followed method of Groen,[22] 2007.

(*continued on next page*)

Table 1 (*continued*)

Author (Year)/ Study Design	Fall Direction	Safe Landing Strategy	Subjects	Fall Simulation Method	Impact Part/Impact Severity Parameter	Fall Strategy Instructions
Groen[24] (2008)/PP	Side	MA fall (rolling and slapping)	N=5 (F=0); Age: 23.8±4.1y	Self-initiated fall in kneeling position	Hip/Impact force; Impact velocity	Followed method of Groen,[22] 2007.
Weerdesteyn[11] (2008)/PP	Side	MA fall (rolling and slapping)	N=10 (F=10); Age: 28.3±6.6y	Self-initiated fall in kneeling position	Wrist/Impact force	A sideways MA 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.
Groen[15] (2010)/PP	Side	MA fall (rolling and slapping)	N=25 (F=19); Age: 69.5±5.9y	Self-initiated fall in kneeling position	Hip/Impact force; Impact velocity; Fall duration	Followed method of Groen,[22] 2007.
Sabick[18] (1999)/PP	Side	Relaxed muscle, slap	N=9 (F=2); Age: NR	Self-initiated fall in kneeling position	Hip/Impact force; Impact velocity	Subjects were told to fall with their body "as relaxed as possible." Also, participants were instructed to perform a slap fall.
Van den Kroonenberg[21] (1996)/PP	Side	Relaxed muscle	N=6 (F=NR); Age: 23.7±3.67y	Self-initiated fall in standing position	Hip/Impact velocity; Impact angle	To investigate the effect of muscle activity on fall dynamics, 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.
Feldman[16] (2007)/Cohort	Side	Stepping	N=44 (F=31); Age: 21±2y	Unexpected translation of surface in standing position	Hip/Fall duration; Impact velocity	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. Values are mean ± SD or as otherwise indicated.
Abbreviations: F, female; NR, not reported; PP, pre-post study; RCT, randomized controlled trial.

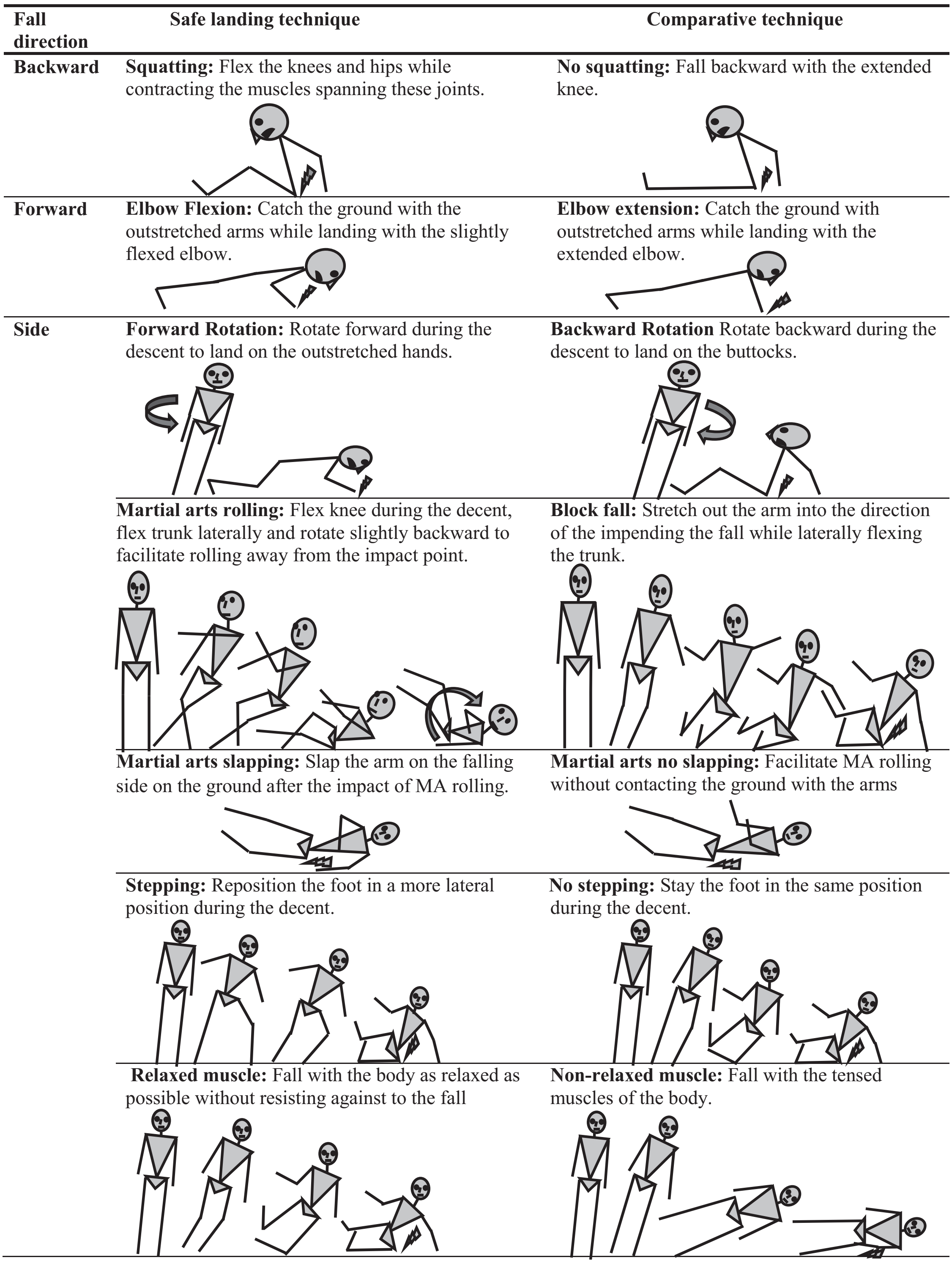

Fig 2 Schematic representation of safe landing techniques and comparative techniques.

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 the body part along the contact path while rolling.[24]

In addition to the dynamic aspect of impact severity, a change of loading configuration could also reduce the risk of injury. The results indicated that MA rolling and relaxed muscles result in less vertical trunk angle at impact and reduce the energy absorbed by the 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 injures. For instance, even unsuccessful attempts to recover balance through stepping were observed to be beneficial in reducing impact severity.[16] Also, forward rotation

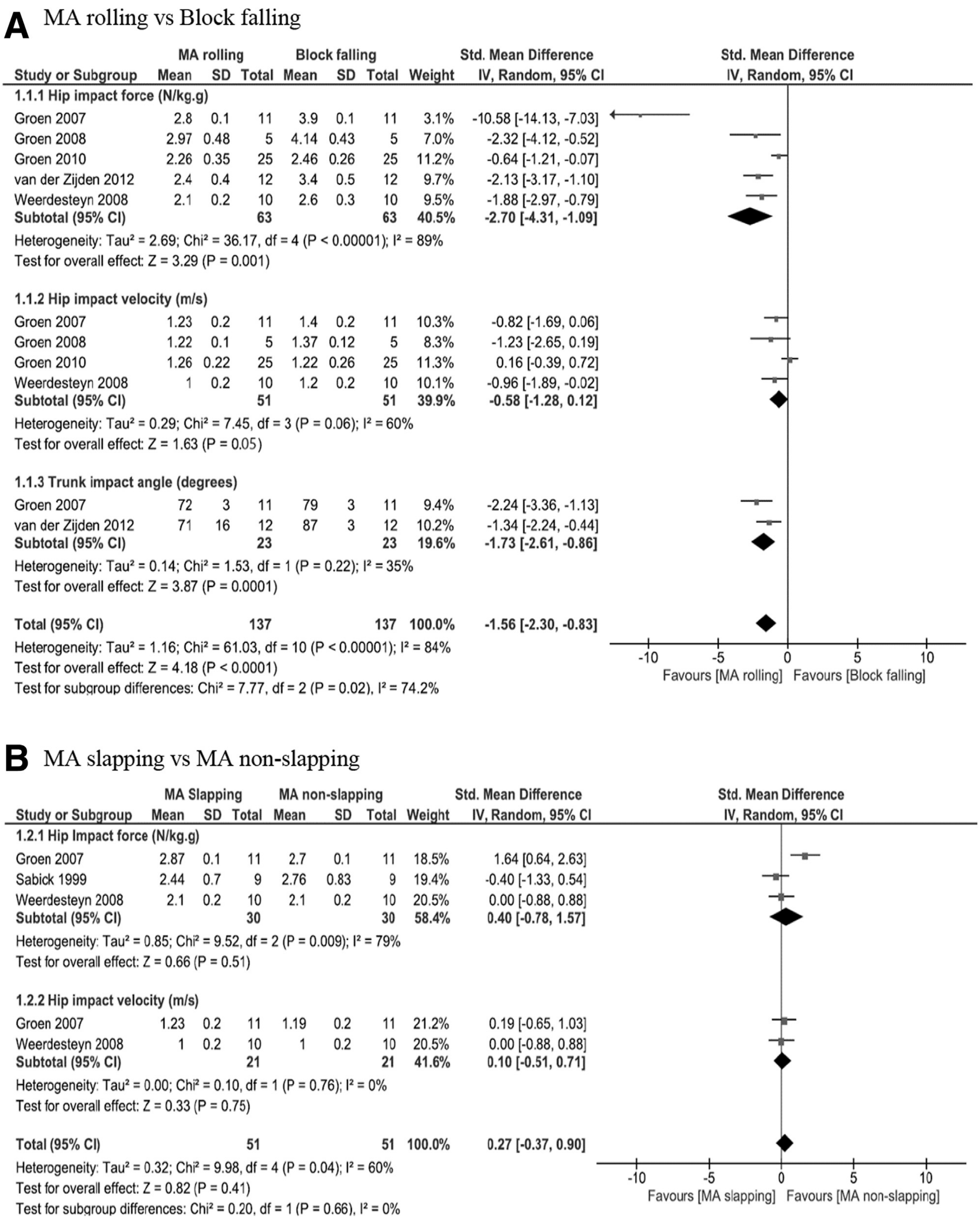

Fig 3 Forest plots of effect of (A) MA rolling and (B) MA slapping to reduce impact severity. Standard mean difference was calculated by Hedges' *g* effect size. Abbreviations: CI, confidence interval; df, degrees of freedom; IV, inverse variance; Std., standard.

during a sideways fall not only dissipates impact energy but also allows subjects to coordinate their movement through visualization of the landing surface before 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.

Table 2 Quantitative effect of protective strategies

Fall Direction	Safe Landing Strategy	Impact Part	Severity Parameter	Statistical Result
Backward	Squatting vs no-squatting	Wrist	Impact velocity	Significantly ↓ (2.27±.30m/s to 2.01±.13m/s)
			Fall duration	Significantly ↓ (873±67ms to 749±72ms)
		Hip	Impact velocity	Significantly ↓ (3.3±0.3m/s to 2.7±0.3m/s)
			Impact energy	Significantly ↓ (307±90J to 172±56J)
Forward	Elbow flexion vs elbow extension when catching the ground	Hand	Impact force	Significantly ↓ (880±40N to 745±42N)
		Wrist	Impact force	Significantly ↓ (11.2±3.6N/kg.g to 8.2±3.4N/kg.g)
			Impact velocity	Significantly ↓ (2.66±.21m/s to 2.52±.15m/s)
		Elbow	Impact force	Significantly ↓ (10.3±6.5N/kg.g to 6.2±11N/kg.g)
		Shoulder	Impact force	Significantly ↓ (32.6±6.5N/kg.g to 24.1±11N/kg.g)
		Neck	Impact velocity	Not significantly different (2.69±.25m/s vs 2.68±.24m/s)
Side	Forward rotation vs backward rotation	Hip	Impact velocity	Significantly ↓ in forward rotation (2.95±.25m/s to 2.45±0.77m/s)
			Impact energy	Significantly ↓ in forward rotation (238±70J to 156±90J)
	MA rolling vs blocking fall	Hip	Fall duration	Not significantly different (246±92ms vs 235±72ms)
			Impact force	Significantly ↓ in 5 of 5 articles (values are provided in fig 3)
			Impact velocity	Significantly ↓ in 3 of 4 articles (values are provided in fig 3)
			Impact angle	Significantly less vertical in 2 of 2 articles (values are provided in fig 3)
	MA slapping vs no-slap when performing MA fall	Hip	Impact force	Not significantly different in 2 of 3 articles (values are provided in fig 3)
			Impact velocity	Not significantly different in 2 of 2 articles (values are provided in fig 3)
			Impact angle	Not significantly different (17°±5° vs 15°±4°)
	Relaxed muscle vs stiffened muscle	Hip	Impact force	Not significantly different (2.76±.83N/kg.g vs 2.69±.68N/kg.g)
			Impact velocity	Significantly ↓ (3.31±.43m/s to 3.09±.41m/s)
			Impact angle	Significantly less vertical (13.6°±11.2° to 21.8°±10.4°)
	Stepping vs nonstepping before falling	Hip	Fall duration	Significantly ↑ (613±53ms to 691±46ms)
			Impact velocity	Significantly ↓ (3.16±.74m/s to 2.46±.94m/s)

NOTE. ↓, reduced; ↑, increased.

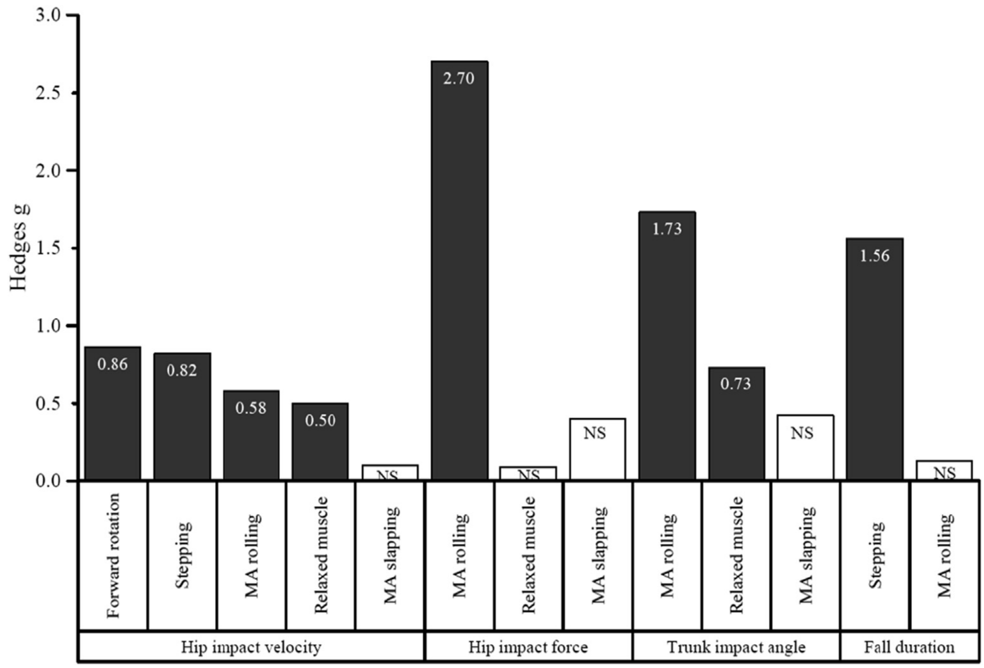

Fig 4 Effect sizes (Hedges' *g*) of sideway safe landing strategies. Abbreviation: NS, nonsignificant effect size.

It has been speculated that elderly individuals have an altered response of falling that leads to an 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 because of reduced muscle strength, delayed reaction time, and belated detection of imbalance.[12,29] Further examination of the influence of aging on the efficiency of safe falling strategies is warranted.

Table 3 Study quality assessment

Criterion	Mean	SD
Was the research question clearly stated?	1.9	0.3
Were the inclusion and exclusion criteria clearly stated?	0.7	0.8
Were the protective landing strategy and comparative strategy clearly stated?	1.9	0.3
Were the main findings of the study clearly described?	1.9	0.3
Did the selected parameters indicate impact severity?	0.8	0.6
Was definition of initial impact well described?	1.4	1.0
Was fall simulation condition clearly stated and uniformly applied to all participants?	1.8	0.4
Was fall simulation protocol appropriate to reflect real-life fall situation?	0.5	0.7
Was a sample size justification via power analysis provided?	0.2	0.6
Were potential confounders (age, sex, height, weight) properly described in the analysis?	1.6	0.7
Total score	13.5	2.7

NOTE. 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.

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] the sideway falls have been the focus of most of the research.

Although previous literature has documented distinctive benefits between safe landing strategies, several limitations have been observed. Only 1 study included elderly subjects, while most 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 MA rolling may be an effective strategy, it may not be practical to teach this technique to individuals at risk of falls. Of note, 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, since 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 a safe landing.[28] Further investigations on safe landing strategies with older adults and clinical populations are essential to generalize the effectiveness of the fall techniques to at-risk populations.

Various parameters were used 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 the time course of the fall.[12] While impact velocity has been used 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] the 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, most studies used self-initiated falls or falls from kneeling height. However, most falls in real life are caused by a sudden loss of balance attributable 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 the ability to modulate impact severity through the protective 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 designs that could reflect real-life falling in a safe manner.

Study limitations

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 criterion standard of impact severity metrics to examine the risk of injury of falling. Lastly, most studies had small or unrepresentative samples, or both, which compromised the generalizability of the study findings.

Conclusions

In conclusion, this study systematically reviewed and quantitatively synthesized findings from existing studies on safe landing strategies. The results showed that all 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 the effectiveness and suitability of the strategies for 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.

Suppliers

a. Stata 14.0 SE version; StataCorp.
b. RevMan 5.3; Cochrane Collaboration.

Keywords

Accidental falls; Movement; Wounds and injuries

Corresponding author

Yaejin Moon, MSc, Department of Kinesiology and Community Health, University of Illinois at Urbana-Champaign, 301 Freer Hall, 906 S Goodwin Ave, Urbana, IL 61801. *E-mail address:* ymoon9@illinois.edu.

Appendix 1 Keyword Search Strategy

Database	Key Terms and Algorithm
PubMed/MEDLINE	(fall OR falls OR "sideways falls" OR "lateral falls" OR "forward falls" OR "backward falls") AND (technique* OR training OR strateg* OR protective OR response* OR reflex) AND ("femoral fracture" OR "hip fracture" OR "hip impact" OR "wrist fracture" OR osteoporosis OR "bone fracture") AND (biomechanic* OR kinematic* OR kinetic* OR EMG OR "muscle activation" OR velocity OR force)
	Refined by: Humans, English
Web of Science	(TS=(fall OR falls OR "sideways falls" OR "lateral falls" OR "forward falls" OR "backward falls") AND TS=(technique* OR training OR strateg* OR protective OR response* OR reflex) AND TS=("femoral fracture " OR "hip fracture" OR "hip impact" OR "wrist fracture" OR osteoporosis OR "bone fracture") AND TS = (biomechanic* OR kinematic* OR kinetic* OR EMG OR "muscle activation" OR velocity OR force))
	Refined by: LANGUAGE: (English)
CINAHL	(fall OR falls OR "sideways falls" OR "lateral falls" OR "forward falls" OR "backward falls") AND (technique* OR training OR strateg* OR protective OR response* OR reflex) AND ("femoral fracture" OR "hip fracture" OR "hip impact" OR "wrist fracture" OR osteoporosis OR "bone fracture") AND (biomechanic* OR kinematic* OR kinetic* OR EMG OR "muscle activation" OR velocity OR force)
	Refined by: English
Cochrane Library	(fall OR falls OR "sideways falls" OR "lateral falls" OR "forward falls" OR "backward falls") AND (technique* OR training OR strateg* OR protective OR response* OR reflex) AND ("femoral fracture" OR "hip fracture" OR "hip impact" OR "wrist fracture" OR osteoporosis OR "bone fracture") AND (biomechanic* OR kinematic* OR kinetic* OR EMG OR "muscle activation" OR velocity OR force)

Abbreviation: CINAHL, Cumulative Index to Nursing and Allied Health Literature.

References

1. Lamb SE, Jørstad-Stein EC, Hauer K, Becker C; Prevention of Falls Network Europe and Outcomes Consensus Group. Development of a common outcome data set for fall injury prevention trials: the Prevention of Falls Network Europe consensus. J Am Geriatr Soc 2005; 53:1618-22.
2. Centers for Disease Control and Prevention. Ten leading causes of death [charts]. 2014. Available at: http://webappa.cdc.gov/sasweb/ncipc/mortrate10_us.html. Accessed February 1, 2014.
3. Stel VS, Smit JH, Pluijm SM, Lips P. Consequences of falling in older men and women and risk factors for health service use and functional decline. Age Ageing 2004;33:58-65.
4. Centers for Disease Control and Prevention. Ten leading causes of non-fatal injury [charts]. 2013. Available at: http://www.cdc.gov/injury/wisqars/LeadingCauses.html. Accessed February 1, 2015.
5. Stevens JA, Corso PS, Finkelstein EA, Miller TR. The costs of fatal and non-fatal falls among older adults. Inj Prev 2006;12:290-5.
6. Orces CH, Alamgir H. Trends in fall-related injuries among older adults treated in emergency departments in the USA. Inj Prev 2014;20: 421-3.
7. Chang JT, Morton SC, Rubenstein LZ, et al. Interventions for the prevention of falls in older adults: systematic review and meta-analysis of randomised clinical trials. BMJ 2004;328:680.
8. Stubbs B, Brefka S, Denkinger MD. What works to prevent falls in community-dwelling older adults? Umbrella review of meta-analyses of randomized controlled trials. Phys Ther 2015;95:1095-110.
9. Gillespie LD, Gillespie WJ, Robertson MC, et al. Interventions for preventing falls in elderly people. Cochrane Database Syst Rev 2003;(4):CD000340.
10. Hsiao ET, Robinovitch SN. Common protective movements govern unexpected falls from standing height. J Biomech 1997;31:1-9.
11. Weerdesteyn V, Groen BE, van Swigchem R, Duysens J. Martial arts fall techniques reduce hip impact forces in naive subjects after a brief period of training. J Electromyogr Kinesiol 2008;18:235-42.
12. DeGoede KM, Ashton-Miller JA, Schultz AB. Fall-related upper body injuries in the older adult: a review of the biomechanical issues. J Biomech 2003;36:1043-53.
13. Robinovitch SN, Brumer R, Maurer J. Effect of the "squat protective response" on impact velocity during backward falls. J Biomech 2004; 37:1329-37.
14. Moher D, Shamseer L, Clarke M, et al. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst Rev 2015;4:1.
15. Groen BE, Smulders E, de Kam D, Duysens J, Weerdesteyn V. Martial arts fall training to prevent hip fractures in the elderly. Osteoporos Int 2010;21:215-21.
16. Feldman F, Robinovitch SN. Reducing hip fracture risk during sideways falls: evidence in young adults of the protective effects of impact to the hands and stepping. J Biomech 2007;40:2612-8.
17. Littell JH, Corcoran J, Pillai V. Systematic reviews and meta-analysis. New York: Oxford Univ Pr; 2008.
18. Sabick MB, Hay JG, Goel VK, Banks SA. Active responses decrease impact forces at the hip and shoulder in falls to the side. J Biomech 1999;32:993-8.
19. Van der Zijden AM, Groen BE, Tanck E, Nienhuis B, Verdonschot N, Weerdesteyn V. Can martial arts techniques reduce fall severity? An in vivo study of femoral loading configurations in sideways falls. J Biomech 2012;45:1650-5.
20. Chou P-H, Chou YL, Lin CJ, et al. Effect of elbow flexion on upper extremity impact forces during a fall. Clin Biomech (Bristol, Avon) 2001;16:888-94.
21. van den Kroonenberg AJ, Hayes WC, McMahon TA. Hip impact velocities and body configurations for voluntary falls from standing height. J Biomech 1996;29:807-11.
22. Groen BE, Weerdesteyn V, Duysens J. Martial arts fall techniques decrease the impact forces at the hip during sideways falling. J Biomech 2007;40:458-62.
23. Lo J, McCabe GN, DeGoede KM, Okuizumi H, Ashton-Miller JA. On reducing hand impact force in forward falls: results of a brief intervention in young males. Clin Biomech (Bristol, Avon) 2003;18:730-6.
24. Groen BE, Weerdesteyn V, Duysens J. The relation between hip impact velocity and hip impact force differs between sideways fall techniques. J Electromyogr Kinesiol 2008;18:228-34.
25. Robinovitch SN, Inkster L, Maurer J, Warnick B. Strategies for avoiding hip impact during sideways falls. J Bone Miner Res 2003;18: 1267-73.
26. Tan J-S, Eng JJ, Robinovitch SN, Warnick B. Wrist impact velocities are smaller in forward falls than backward falls from standing. J Biomech 2006;39:1804-11.
27. Stevens JA, Mack KA, Paulozzi LJ, Ballesteros MF. Self-reported falls and fall-related injuries among persons aged>or=65 years—United States, 2006. J Safety Res 2008;39:345-9.
28. Kim K-J, Ashton-Miller JA. Biomechanics of fall arrest using the upper extremity: age differences. Clin Biomech (Bristol, Avon) 2003; 18:311-8.
29. Sran MA, Stotz PJ, Normandin SC, Robinovitch SN. Age differences in energy absorption in the upper extremity during a descent movement: implications for arresting a fall. J Gerontol A Biol Sci Med Sci 2010;65:312-7.
30. Parkkari J, Kannus P, Palvanen M, et al. Majority of hip fractures occur as a result of a fall and impact on the greater trochanter of the femur: a prospective controlled hip fracture study with 206 consecutive patients. Calcif Tissue Int 1999;65:183-7.
31. Thurman DJ, Alverson C, Dunn KA, Guerrero J, Sniezek JE. Traumatic brain injury in the United States: a public health perspective. J Head Trauma Rehabil 1999;14:602-15.
32. Choi WJ, Robinovitch SN. Pressure distribution over the palm region during forward falls on the outstretched hands. J Biomech 2011;44: 532-9.